Declaration

I declare that this thesis contains no material which has been accepted for the award of any other degree or diploma in any tertiary institution, and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

Janelle Agius

Abstract

Limnopolar Lake, Livingston Island, situated close to the tip of the northern Antarctic Peninsula (62°40'S, 61°00'W), has experienced a long history of primary and secondary tephra inputs from nearby volcanic centres. Background levels of tephra in a sediment core collected from the lake were ~30,000-35,000 g_{dm}^{-1}, and were caused by the continual washing in of tephra deposited in the surrounding watershed. Tephra abundances above these levels were assigned to tephra horizons, of which 5 were identified to have occurred over the last 2000 years. Electron probe microanalysis of the tephra shards revealed that the predominant composition of the tephra was basaltic andesite, with few basalt and andesite pyroclasts. Limited numbers of shards with trachy-basalt and basaltic trachy-andesite compositions were also recorded. Deception Island was attributed as the most likely source of the tephra.

Eight distinct biological communities were identified in the sediment core on the basis of abundance and distribution of organism remains. Most community shifts over the last ~2000 years appear to be due to direct or indirect effects of tephra deposition into the lake, with tephra abundance levels being an important factor. However, some community shifts can be attributed to climate variability and grazing pressures. The apparent lack of zooplankton species, with only a recent colonisation of the anostracan *Branchinecta gainii* and possibly the copepod *Boeckella poppei*, suggests that zooplankton species may not be adapted to surviving in lakes with continual tephral inputs or alternately have recently colonised the island.

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Chapter One

INTRODUCTION

1 Cataclysmic events

Natural disturbances have always been a part of the Earth's history. Naturally occurring events such as large-scale climate shifts, bushfires, tsunamis, floods, meteorite impacts, earthquakes and volcanic eruptions produce significant impacts upon the surrounding environment (Summerfield, 1997; Christopherson, 2000). These events particularly affect flora and fauna through dramatic changes to various habitats in very short time scales. If large enough, these processes can create global cataclysmic events such as the extinction of the dinosaurs thought to be caused by a meteorite impact at the Cretaceous-Tertiary boundary (Monroe and Wicander, 1997). However, smaller-scale natural disturbances can also create devastating events within local biomes.

This study examines the effects of nearby volcanic eruptions on the biota of a freshwater Antarctic lake. Tephra is the term given to solid material that is ejected during explosive eruptions and is transported via aerial processes. Tephra inputs into a lake environment either directly deposited or indirectly washed in from the local watershed, can create significant impacts to the physical and chemical properties of a lake, which could significantly affect biota in the lake.

1.1 Tephra

Tephra studies are based on the physical and chemical characteristics of tephra layers within the sediment record, with the assumption that tephra layers are deposited

instantaneously (in geologic terms), and that each tephra deposit possesses unique geochemical signatures (Hunt and Hill, 1993; Narcisi *et al*., 2005).

Tephra layers are common within marine and lacustrine sediment cores, as well as within ice cores from around the Antarctic. Tephrostratigraphy and tephrochronology are the most important existing tools used to identify correlations and dating between ice and sediment cores, especially in regions such as the Antarctic where conventional dating techniques (eg radiocarbon dating) are insufficient (Björck *et al*., 1991d; Smellie, 1999).

Ice cores are valuable archives of past volcanic history as snow layers simultaneously incorporate both the gaseous and tephra products of a volcanic event. This means that volcanic activity can be identified in the absence of solid ejected material (Narcisi *et al*., 2001; Narcisi *et al*., 2005). Tephra layers within sediment records provide insights into biotic and abiotic responses to tephra inputs into lake environments.

1.2 Impacts of tephra on lake ecosystems

Volcanism has always played an important role throughout the Earth's history. Eruptions have the potential to produce climate changes and although they can destroy complete habitats they can also create new environments for colonisation.

Organisms within lake communities are not only affected by direct inputs of tephra into a lake and its watershed system, but also by atmospheric interactions with the pyroclastic cloud producing acidic precipitation and forcing climatic fluctuations (Birks and Lotter, 1994).

Explosive volcanism has long been recognised as one of the three most important factors affecting the decadal climatic system, along with solar variability and interactions between the ocean and atmospheric cycles (Cole-Dai *et al*., 1997; Zhang *et al*., 2002). Major volcanic eruptions produce large amounts of sulphur dioxide and other gases. The sulphur dioxide is oxidised in the atmosphere to form sulphuric acid and water aerosol particles (Cadle *et al*., 1976; Dai *et al*., 1991; Robock, 2000).

These aerosols can be spread globally through the atmosphere where it has the potential to produce acid precipitation for several years after the volcanic eruption. The aerosols may also significantly alter the radiative balance and albedo of the Earth and atmosphere, creating short-term climatic impacts (Gow and Williamson, 1971; Kyle *et al*., 1981; Moore *et al*., 1991; Cole-Dai *et al*., 2000; Zielinski, 2000). For example, following the Mt. Pinatubo eruption, a decrease of 0.2-0.7 °C was recorded in the global tropospheric and near surface temperatures, with a corresponding increase in stratospheric temperatures that lasted for several years (Cole-Dai *et al*., 1997).

Ecologists are interested in volcanic eruptions due to their potential to alter complete landscapes and their associated biota in very short time periods. The preservation of tephra layers within lake environments provide a unique opportunity to investigate the effects of past eruptions on the biota of the lake and the timing of recovery of various organisms and the ecosystem as a whole (Barker *et al*., 2000; Eastwood *et al*., 2002; Hotes *et al*., 2004). There are many views on the duration and severity of various effects on lake ecosystems due to tephra deposition. There is scope for variation, as each lake belongs to its own watersheds, with differing biotic and abiotic factors, that will determine the effects of tephra deposition within that environment (Hotes *et al*., 2004).

A number of palaeolimnological studies have shown important ecosystem responses to tephra deposition. Most reveal dramatic changes within the lake system as it is forced to shift into a new state of equilibrium, requiring an adjustment/recovery phase, followed by a period of chronic ecosystem change (Ward *et al*., 1983; Lotter *et al*., 1995; Barker *et al*., 2000). Some studies reveal large increases or decreases in organism abundances after tephra deposition, whilst others show changes only in dominant organisms within the lake. Many of these changes are due to a combination of direct and indirect effects of the deposition of tephra into the lake and its surrounding water catchment (Barker *et al*., 2000).

One virtually instantaneous response to the lake environment upon tephra deposition is a reduction in light and an increase in turbidity. Given the settling velocities of fine tephra shards as predicted from Stoke's Law (~75 m d^{-1}), this effect is assumed to be

short-lived (Barker *et al.*, 2000). However, the period of light reduction and turbidity may be increased due to the washing-in of tephra from the surrounding watershed, which will continue until the catchment soils are depleted of tephra (Abella, 1988; Björck *et al.*, 1993). This also makes it difficult to distinguish other environmental or climatic signals that may be affecting the lake ecosystem (Björck *et al.*, 1993). More prolonged changes within the lake ecosystem could be explained via nutrient resource availability, chemical weathering of tephra, sealing of the sediment-water boundary, or burial of lake plant and other benthic communities (Birks and Lotter, 1994; Hickman and Reasoner, 1994; Lotter *et al*., 1995; Tatur *et al.*, 1999; Eastwood *et al*., 2002).

Changes of pore water chemistry and increased ionic concentrations depend largely upon the amount of leaching of tephra shards and the chemical constituents of individual shards (Heinrichs *et al.,* 1999; Hotes *et al*., 2004). Tephra leachants may contain biologically-important metals and compounds such as iron, molybdenum, manganese, sulphate, silica, nitrogen and phosphorus. Inorganic nitrogen and phosphorus ratios, along with silica, are usually used as indicators of nitrogen and phosphorus limitation or silica enrichment to biological processes (Ward *et al.,* 1983; Abella, 1988; Crowley *et al*., 1994).

Planktonic diatom communities are extremely sensitive to most environmental conditions and respond by changes in growth rates, abundance and species composition, however, the complicated effects of tephra deposition make it difficult to identify the specific causes of diatom community alterations (Abella, 1988; Hickman and Reasoner, 1994; Metcalfe, 1995). Following tephra deposition there is a large increase of silica within the lake system due to the dissolution of the tephra shards, and phosphorus is reduced from the sediment-water interface (Lotter *et al*., 1995). Studies carried out by Barker *et al*. (2000) found that many diatom species undergo resource competition post-tephra deposition and found that phosphorus limitation was more important to the diatom assemblages than silica enhancement. Studies carried out by Abella. (1988) also identified the Si:P ratio to be an important factor in diatom communities and found that changes within lake communities after the Mount Mazama, Oregon, eruption (6800 years before present (BP)) were species specific and dominated by nutrient requirements and tolerance levels of each species.

The eruption of Mount St Helens in 1980 prompted several studies of volcanic influences on the biology and chemistry of aquatic environments. Investigations showed that the fallout from volcanic events has severe and prolonged influences on the biota of nearby lakes and watersheds, with the magnitude of impacts being dependent on proximity to the volcanic source (Heinrichs *et al.,* 1999). Metal concentrations due to leaching of tephra remained high in all lakes, though the associated pH levels were difficult to determine due to buffering by carbonic acid, dissolved organic matter and biological processes (Ward *et al*., 1983; Crowley *et al*., 1994). Investigations carried out by Ward *et al.* (1983) found that the influx of tephra resulted in severe light limitations within the water column and was attributed to the slow development of phytoplankton within the lakes in the months following the eruption. Within only 3-4 months of the Mount St Helens eruption many different species of algae had already begun colonising many of the lake systems (Ward *et al*., 1983). Lotter and Birks. (1993) suggested that the effects of tephra might therefore be important within lake ecosystems for approximately 2-20 years due to the rapid colonisation that took place within lakes affected by the Mount St Helens eruption (Lotter and Birks, 1993; Hickman and Reasoner, 1994).

1.3 Possible impacts of tephra on lake abiotic factors

1.3.1 Light and turbidity

Factors influencing the penetration of ultraviolet radiation into lake environments vary temporally and spatially even within relatively small lake systems (Kepner *et al*., 2000). Solar radiation provides the major energy input into lake environments. Plants use the radiant energy during photosynthesis via biochemical processes. The rate of photosynthesis is proportional to the amount of light penetration and scattering within the water column (Cohen, 2003; Brönmark and Hansson, 2005). The absorption of energy and the dissipation of heat have profound effects on thermal stratification, nutrient cycling, distribution of dissolved gases and biota within the lake (Wetzel, 2001; Brönmark and Hansson, 2005). Humic substances and inputs into the lake, such as tephra, will decrease pH, dissolved oxygen, and light penetration levels within the water column (Brönmark and Hansson, 2005).

Turbidity is a visual property of water that implies a reduction or lack of clarity that results from the presence of suspended particles, typically inorganic particles. Turbidity increases the scattering of solar radiation, which enhances reflection and scattering of light back into the atmosphere (Wetzel, 2001).

1.3.2 pH

pH is a measure of the acidity of a solution. Lakes display regional differences in pH levels, as acidification is a result of basin bedrock mineralogy, hydrology of the catchment area, input of acidifying substances, and productivity of the lake system (Brönmark and Hansson, 2005). Acidification of lakes has profound biological consequences in lake ecosystems. Most lake organisms are sensitive to changes in lake acidity. Extreme acidification affects many physiological processes in lake fauna and flora (Cohen, 2003). When the pH in a lake reaches values lower than six, ecosystem changes begin to take place. Algal species diversity decreases considerably when pH levels are below 6 due to the disappearance of cyanobacteria and diatoms. Fauna also becomes less diverse at pH levels below 6 as the reproduction of many organisms is affected (Brönmark and Hansson, 2005).

The pH of freshwater lakes within volcanic regions may be as low as 2 as a result of the input of strong mineral acids such as sulphuric acid. Among zooplankton, daphnids are severely affected by acidification, whilst the abundance of other cladocerans may remain high. Rotifers as well as some insect larvae are also often abundant in acidified lakes (Cole, 1979; Brönmark and Hansson, 2005).

1.3.3 Temperature

Water has a high heat storage capacity resulting in changing diurnal and seasonal temperature profiles within lakes. As most freshwater organisms are poikilothermic, temperature is a key environmental factor affecting distribution patterns, behaviour, metabolic rates, and reproduction of organisms (Brönmark and Hansson, 2005). The depth to which various wavelengths of light penetrate the water column and how the

light is scattered and absorbed may be greatly affected by the input of tephra, and may therefore affect temperature gradients within the lake (Cohen, 2003).

1.3.4 Dissolved Oxygen

Oxygen is a necessary requirement for all organisms with aerobic respiration, which includes the majority of freshwater heterotrophs. The amount of oxygen in solution at any time is sensitive to changes in chemical processes within the lake. Changes in lake chemical processes that regulate oxygen concentrations may be effected by the dissolution of ionic substances from tephra particles. The development of low oxygen concentrations would result in a severe deterioration of living conditions for most freshwater organisms (Brönmark and Hansson, 2005).

1.4 Palaeolimnology

Determinations can be made on the possible impacts of tephra in a lake community through examining the history of the lake preserved within its sedimentary record. Limnology is the science that investigates the structure and function of inland bodies of water (Lampert and Sommer, 1997). Lakes tend to respond quickly to external or internal forcing variables due to their relatively small areas and volumes. Palaeolimnologists therefore study lake sediment archives as they provide insights into environmental conditions and associated changes in lake productivity, such as climate, volcanic activity and lake ecosystem interactions (Lampert and Sommer, 1997; Cohen, 2003).

Lakes are typically defined as being enclosed bodies of water surrounded by land with watershed of varying areas depending on lake settings, most being large in comparison to the lake area. As a result of these large watersheds, lake environments generally have relatively rapid sedimentation and accumulation rates as opposed to marine or other terrestrial settings (Cohen, 2003). Understanding the evolution of a lake basin and its surrounding catchment area is therefore an essential requirement of palaeolimnology studies.

1.5 Sedimentary record

Remains of organisms from the lake, as well as pollen and spores from terrestrial plants within the catchment, and nearby areas, settle on the lake sediment surface producing in many cases high-resolution chronological records within the sediment. Remains of invertebrates within the sediment cores can be used to re-construct lake histories. Whilst some organisms, such as cladocerans and diatoms, have hard components that are well preserved, other organisms with softer body parts may not preserve at all. In some cases, especially zooplankton, only small fragments of the organism such as claws, mandibles or resting eggs may be preserved (Brönmark and Hansson, 2005).

Changes and fluctuations within these remains can be used to identify organism adaptations, invasion and colonisation of endemic and non-endemic species. This is an important factor in palaeolimnology that allows ecosystem interactions and changes to environmental conditions to be fully understood.

A number of characteristics and adaptations of lake organisms may make it less demanding for these organisms to survive through tephral input into the lake. This thesis focuses on particular characteristics and adaptations of Antarctic lake biota, as this is where the study site is centred. Additionally, the Antarctic is a stressful environment for lake biota to survive in. The adaptations that these organisms already posses to survive within the Antarctic may prove to be advantageous in coping with the stresses imposed by the input of tephra into the lake.

1.6 Endemism and succession

The Antarctic continent has been isolated from the rest of the world by a wide oceanic belt, located approximately 40°S-65°S, for at least the last 10 million years. The Antarctic landscape is dominated by large-scale habitat fragmentation with little more than 1% of the 14 million square kilometres of the continent being ice-free today (Stevens and Hogg, 2003). Freshwater lakes occur in many Antarctic ice-free areas and are characterised by short food chains that are dominated by microbes. This reflects their low productivity and isolation from other freshwater ecosystems within

the Antarctic and from surrounding continents (Jones *et al.,* 1993; Ellis-Evans, 1996b; Butler *et al.,* 2000; Wilson *et al.*, 2002; Hansson and Tranvik, 2003). In many cases the highest organisms present in Antarctic lakes are unicellular, however, in locations such as some east Antarctic areas, the Antarctic Peninsula, and sub-Antarctic islands, complexity increases through the presence of one or more higher order animals (Ellis-Evans, 1996b; Sabbe *et al.*, 2004).

It is clear that the last 700,000 years have been dominated by major ice ages that have been interrupted by relatively short interglacials on a roughly 100 000 year cycle, leading to more than 10 major glacial cycles during the last million years. These severe changes in climate conditions have profound effects on the survival of flora and fauna within Antarctic freshwater lake communities (Hewitt, 1996). The process of colonisation of freshwater Antarctic lakes since the last glacial maximum has been the subject of conjecture. It is not certain whether species currently present survived in local refugia, such as lakes associated with nunataks or epishelf lakes, or if species have re-invaded from sub-Antarctic islands or continents to the north (Swadling *et al*., 2001; Cromer *et al*., 2005).

1.7 Invasion and dispersal

Genetic studies have proven that some species inhabiting Antarctica are endemic to the continent whilst others are non-endemic and have dispersed to Antarctic lake environments since the conclusion of the last glacial maximum (Vincent *et al.*, 2000). Phylogeographic studies of freshwater lake environments have therefore become critical in the understanding of lake histories, evaluation of potential refugial habitats, and ecosystem reactions during periods of glaciation (Cox and Hebert, 2001).

Transport mechanisms for the invasion of non-endemic species include atmospheric circulation, birds and mammals. These transport mechanisms can operate over long distances such as across the Southern Ocean, and they also allow for the dispersal of organisms, both endemic and non-endemic, around the Antarctic continent and sub-islands. This allows gene flow from outside the Antarctic and can be especially important during periods of climate change when new habitats may become available

for re-colonisation from local refugia such as nunataks, epishelf lakes, or cryoconite holes (Vincent *et al.*, 2000). Additionally, asexual reproduction, parthenogenesis, or hermaphroditism should increase the probability of successful dispersal, as a single individual is then sufficient to start a new population (Everitt, 1981; Brönmark and Hansson, 2005).

There are four main scientific investigations that have shown the importance of atmospheric circulation processes on the dispersal of microbiota: (1) Researchers have found snow in the maritime region of Antarctica containing South American algae and a spore trap confirmed that the pollen was intermittently dispersed by the wind. (2) The Antarctic ice-sheets were found to contain species of microbiota that have not appeared as living cells in present-day Antarctic habitats, indicating that they must have been transported by wind currents from outside the Antarctic region. (3) Large distances separate geothermal habitats, yet communities contain assemblages of microbial species that not only resemble one another, but also resemble those from other zones (Vincent *et al*., 2000). (4) Freshwater habitats contain many cosmopolitan species of fungi, micro-algae, bacteria and protozoa, suggesting a frequent aerial exchange with other landmasses (Vincent *et al*., 2000).

The aerial connectivity between the northern Antarctic Peninsula and temperate latitudes is likely to be much higher than the rest of the Antarctic continent due to the lesser distance of separation from adjoining landmasses (Butler *et al.*, 2000; Vincent *et al*., 2000). However, data collected from constant pressure balloons (Fig. 1.1) shows that an air mass can pass over South America, over all of the sub-Antarctic islands, as well as most parts of the continent within 8 days (Ellis-Evans and Walton, 1990).

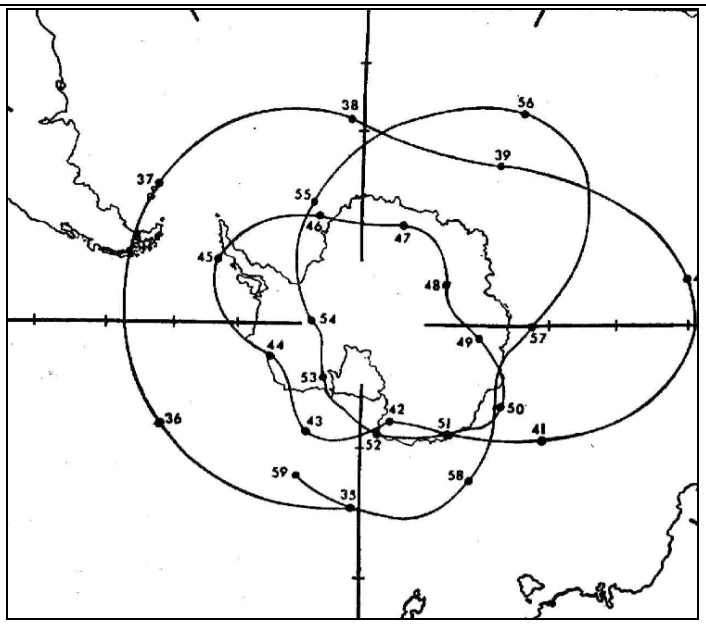

Figure 1.1. Track of constant pressure balloon 10-12 km around Antarctica. The numbers indicate days 35-59 since release (Ellis-Evans, 1990).

Only those species that are resistant to desiccation and broadly tolerant to varying temperatures, or those that produce highly resistant resting eggs, are likely to be dispersed by aerial or animal vectors (Swadling *et al*., 2001). Many Antarctic lake organisms posses these qualities, for example, cyanobacteria and tardigrades are resistant to desiccation and therefore can be dispersed via wind circulation over short (10-1000s m) distances. Furthermore, resting eggs of zooplankton allow both temporal and spatial dispersion and are therefore an important asset for colonisation (Nelson and Marley, 2000). The split of Pangaea into Laurasia and Gondwana defined the first geographical dispersal of cladocerans. The ability for the organism to reproduce parthenogenetically and to create transportable eggs that are resistant to desiccation, extreme temperature changes, corrosion or biodegradation makes dispersal easier and more successful for these organisms than for some other crustaceans such as copepods (Korhola and Rautio, 2001). Tardigrades are also most likely to be Pangaean in origin as it is unlikely that the organism can be transported by long-range aerial dispersal due to their size and weight (McInnes and Pugh, 1998).

1.8 Adaptation and dormancy

Organisms inhabiting any one lake are only a subset of all freshwater organisms, as most organisms will only appear in certain lakes that provide very specific living

conditions, whilst others can inhabit a broad range of systems. Only organisms that are adapted to a certain lake environment will survive under those conditions and will be able to colonise and reproduce successfully (Brönmark and Hansson, 2005).

Most Antarctic lakes are frozen, to a depth of 1-2 m, for approximately 10-12 months of the year and therefore organisms present within a lake community experience less variable environmental conditions than that outside the lake as the ice acts as a buffer (Ellis-Evans, 1996; Robinson *et al*., 2003). However, Antarctic lakes undergo large annual fluctuations in the amount of photosynthetically active radiation due to the high latitudes and winter ice and snow cover. Water temperatures are also permanently low and sources of potential colonising organisms are remote (Jones *et al.*, 1993; Butler, *et al*., 2000). The ability for organisms to overcome stress factors such as freeze-thaw cycles, desiccation, exposure to ultraviolet light and continuous irradiance is essential for an organism's survival in Antarctic lake communities (Tang *et al*., 1997).

For survival in the Antarctic conditions organisms need to either be adapted to low temperatures (psychrophilic) or tolerant of low temperatures with sub-optimal growth at lower temperatures (psychrotrophic) (Tang *et al*., 1997). Studies on true Antarctic psychrophiles indicate that changes in specific enzymes show a competitive advantage at low temperatures; however, when temperatures are variable this advantage disappears and the more flexible psychrotrophs become more dominant (Ellis-Evans and Walton, 1990). Cyanobacteria are well adapted for survival in these environments as they can survive freeze-thaw cycles very efficiently through their ability to control light fixation (Tang *et al*., 1997).

Dormancy has proven to be an essential function in the survival of organisms during periods of extended seasonal ice cover or glacial periods, for example, organisms that produce diapausing eggs have a higher rate of long-term survival over other organisms (Brönmark and Hansson, 2005). Dormancy is a state of suppressed development with the extremes of quiescence and diapause. Quiescence is an immediate direct response to a limiting factor such as temperature, salinity, or oxygen, with development resuming with the resumption of favourable conditions. Diapause on the other hand, is a profound metabolic interruption that is created by an

organised halt in development. Both of these mechanisms are advantageous when surviving and colonising Antarctic freshwater lakes. Dormancy has been reported in a number of zooplankton including cladocerans and copepods and has also been documented in rotifers and tardigrades (Lampert and Sommer, 1997; Brönmark and Hansson, 2005).

Reproduction in many of the zooplankton found within freshwater Antarctic lakes has been adapted for survival in this environment. During suboptimal conditions such as overcrowding, limited food availability, intolerable temperature variance, or oxygen depletion in the water column, several organisms form resting stages, which are generally thick-walled cysts. These cysts are able to withstand various adverse environmental conditions including suboptimal temperatures, anoxic conditions, exposure to fungal and bacterial growth, and almost dry conditions since they remain viable with the aid of pore water trapped between sediment particles (Brönmark and Hansson, 2005). Non-encysted dormant copepods can survive on stored lipids whilst drifting with plankton during periods of poor environmental conditions (Wetzel, 2001).

Some zooplankton species form egg banks at the sediment surface that will hatch in more favourable conditions. Internal factors, such as genetically programmed timing, and external factors, such as physical and chemical conditions, are involved at some stage during these processes. An egg or cyst bank functions as a time-dispersal system that allows for rapid colonisation, and serves as a major genetic reservoir following a catastrophic event (Hairston *et al*., 1995; Brönmark and Hansson, 2005).

Many freshwater lake organisms have a period of diapause, which is a stage of arrested development and reduced metabolic rate. The eggs in ephippia of cladocera are an example of such a diapausing stage, for the eggs cease development (Lampert and Sommer, 1997). For example, during most of the growing season the reproduction of cladocerans is via parthenogenesis. When environmental conditions deteriorate males are then produced parthenogenetically and then diapausing eggs are generated sexually (gametogenesis) (Lampert and Sommer, 1997).

The high resistance the eggs possess against desiccation, extreme temperature changes, digestion, or biodegradation further aids the reproduction and colonisation of the species. Diapausing eggs can remain viable in aquatic sediments for decades, or longer, and have a mortality rate of 1% per year (Wetzel, 2001). The properties of these diapausing eggs will provide a greater chance for that species survival during tephral inputs into the lake environment.

1.9 Project objectives

The main objective of this thesis is to examine tephra inputs into a lake environment on the South Shetland Islands, Antarctic Peninsula, to ascertain what types of impacts this may create for lake organisms and how it may affect the overall lake ecosystem. The primary goals of this project are:

- To extract and geochemically identify tephra shards from the sediment core. This will enable correlations to be made with tephra deposits from the surrounding area, as well as aiding in locating possible source volcanoes.

- Determining tephra input loads in the lake environment. This will help to identify the tolerance levels of various organisms to tephra inputs.

- Identify possible ecological responses to tephra inputs through examining organism remains within the sediment core and comparing with tephra results.

1.10 Thesis Structure

Chapter Two introduces the study site including information regarding geographical location, geology, geomorphology, and glaciology, which have led to a rich scientific history of the region. Information on the study lake is also given in this chapter. Chapter Three provides background information concerning the physical aspects of

this study, including an introduction on tephra, how it is formed and transported, and general information regarding tephra deposits in the Antarctic. Background information is also provided for organic carbon and carbonate content within the sediment core as these variables can give indications of tephra impacts and biotic responses. Chapter Four focuses on background information regarding various freshwater organisms found within Antarctic Peninsula lake communities, as it is important to understand physiological characteristics of an organism to predict possible implications caused by tephra inputs. Chapter Five provides an outline of the methods and procedures undertaken within this study. Chapter Six presents data from physical analyses of the sediment core, whilst Chapter Seven presents data for the ecological analyses. Chapter Eight combines these two data sets to discuss and determine the impacts of tephra and biotic responses. Chapter Nine provides a summary of the main findings of this study including suggestions for future research.

Chapter Two

STUDY SITE

2 Introduction

This chapter provides some general background on Livingston Island, focusing on Byers Peninsula where the study lake is located. The geology, geomorphology and the vast array of lakes have led to a rich scientific history for Byers Peninsula. General information is also presented for the study lake, Limnopolar Lake, including its geographical location, length, width, area and depth.

2.1 Geographical location

Livingston Island is the second largest of the South Shetland Islands and lies approximately 100 km north of the Antarctic Peninsula and roughly 70 km southwest of King George Island (Fig. 2.1) (Björck *et al.*, 1991a; Thomson and López-Martínez, 1996). The northern coast of Livingston Island is bordered by the Drake Passage and the southern coast by the Bransfield Strait.

There are two permanent bases on Livingston Island: Juan Carlos I Station and St. Kliment Ohridski Station (Fig. 2.1). Juan Carlos I Station is a Spanish base located at 62°39′S, 60°23′W, and was established in 1988. Approximately 2 km south of Juan Carlos I Station is the Bulgarian St. Kliment Ohridski Station, established in 1994. Twenty to thirty personnel usually occupy both bases during the summer.

Byers Peninsula is located at the western end of Livingston Island and is the largest ice-free area of the South Shetland Islands (Fig. 2.1 and 2.2). The peninsula is bounded to the east by an ice cap, which covers Rotch Dome, a summit 360 m above

sea level (a.s.l) (Jones *et al*., 1993; Thomson and López-Martínez, 1996). Byers Peninsula has a total area of 60.6 km^2, of which only 0.5 km^2 is covered by ice in the form of three small, remnant glaciers (Thomson and López-Martínez, 1996).

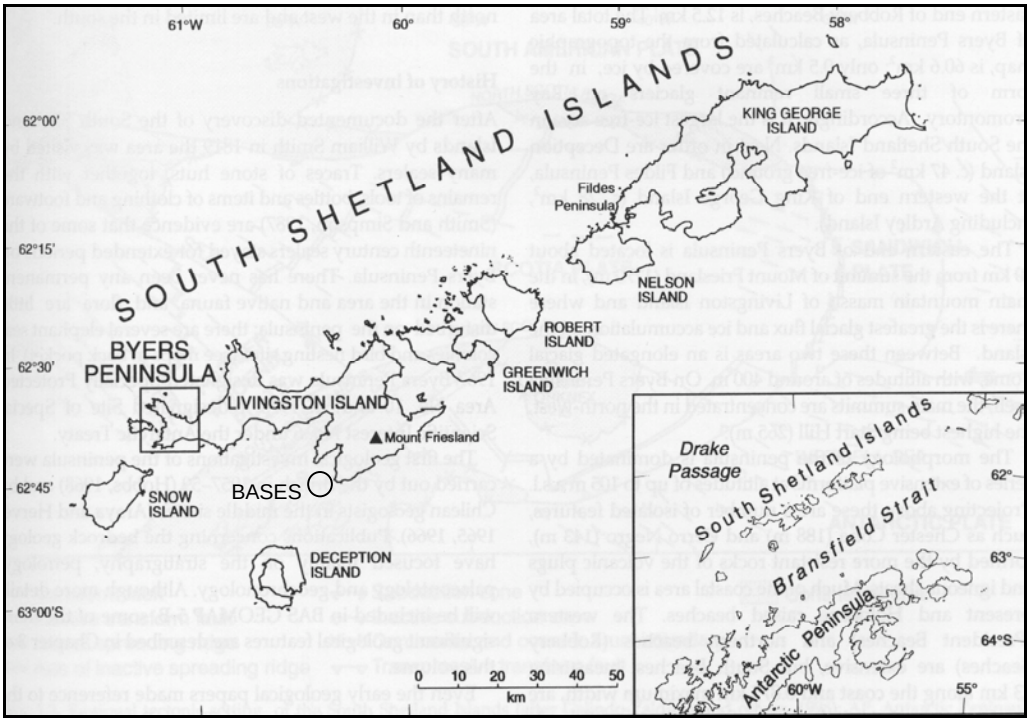

Figure 2.1. Map of the South Shetland Islands, with Byers Peninsula (Livingston Island) indicated by inset box, expanded in Figures 2.2; 2.3; 2.5. Inset circles highlight the location of the two permanent bases on Livingston Island (Thomson and López-Martínez, 1996).

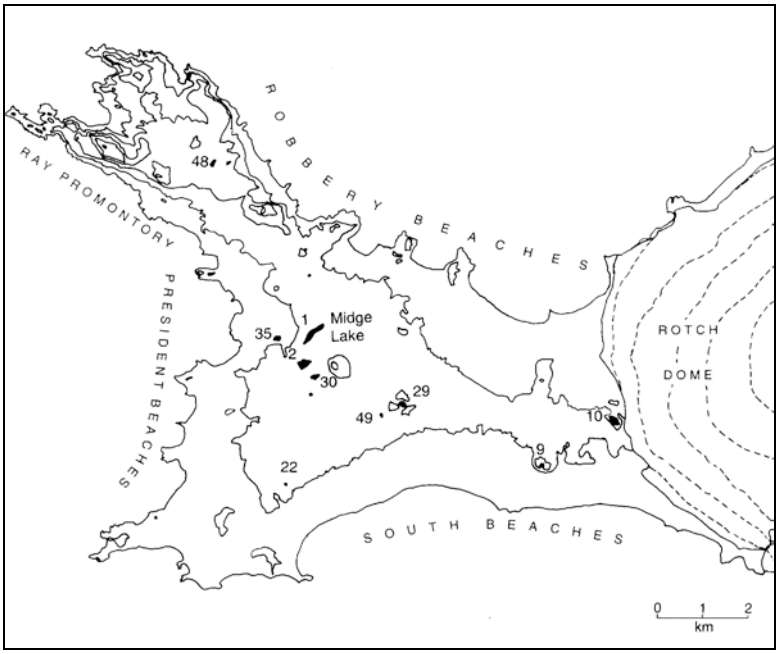

Figure 2.2. Basic topographic map of Byers Peninsula, Livingston Island (Björck and Zale, 1996).

2.2 History of scientific investigation

The native flora and fauna on Byers Peninsula is virtually undisturbed, with the presence of several elephant seal colonies and bird nesting sites leading to the area being designated a Specially Protected Area in 1967. The interesting geology, geomorphology, glacial history, and limnological significance of the Peninsula led to its re-designation as a Site of Special Scientific Interest, under the Antarctic Treaty, in 1975 (Thomson and López-Martínez, 1996; Rico *et al.*, 2003).

The first geological investigations, concerning stratigraphy, petrology, palaeontology, and geochronology, were carried out by the British in 1957-69 and by Chilean geologists in 1965-67. Geomorphological features were recognised during these studies leading to a more complete geomorphologic profile of Byers Peninsula by 1971 (Thomson and López-Martínez, 1996). The discovery that the lakes on Byers Peninsula revealed important information about Late Holocene palaeoclimatic and de-glaciation history has led to an array of limnological studies beginning in 1991 (Thomson and López-Martínez, 1996). The multitude of studies, covering many disciplines, led to the production of a detailed geomorphological map of Byers Peninsula and an accompanying book containing thorough complementary notes in 1996 (Thomson and López-Martínez, 1996).

Current limnological studies on Byers Peninsula are being carried out by a Spanish research group, Limnopolar, under the direction of Dr Antonio Quesada from the Universidad Autonoma de Madrid. This research project is investigating lake ecosystems and how they may react to potential climate change, allowing predictions of expected ecological variations following a large-scale climate shift. Further information regarding this research group and preliminary results can be found on the Internet (http://www.uam.es/proyectosinv/antartid/presentacesp.htm). Dr Antonio Quesada provided the sediment core, collected from Limnopolar Lake, for analyses during this study.

2.3 Geology of Byers Peninsula

The South Shetland Islands occupy a small tectonic plate (Shetland Tectonic Block) located between the South Shetland Trench and Bransfield Strait. Bransfield Strait is a Neogene back-arc basin that contains a linear chain of volcanic seamounts, the largest being Deception Island, which is located 25 km southeast of Byers Peninsula (Fig. 2.1) (Baker, 1990; Gracia *et al.*, 1996; Galindo-Zaldivar *et al.*, 1996; Smellie and López-Martínez, 2002).

The bedrock is composed of Upper Jurassic to Lower Cretaceous marine sedimentary units (Byers Group) overlain unconformably by volcanic and volcaniclastics that are intruded with igneous bodies (Fig. 2.3), representing a Mesozoic-Cenozoic magmatic arc complex that is exposed throughout the Antarctic Peninsula (Smellie *et al.*, 1980; Jones *et al.*, 1993; López-Martínez *et al.*, 1996a; Sell *et al.*, 2004). The structure of southern and eastern Byers Peninsula is controlled by a series of ENE-striking faults (normal) resulting in the progressive south-westward offset of lithological units (López-Martínez *et al.*, 1996a).

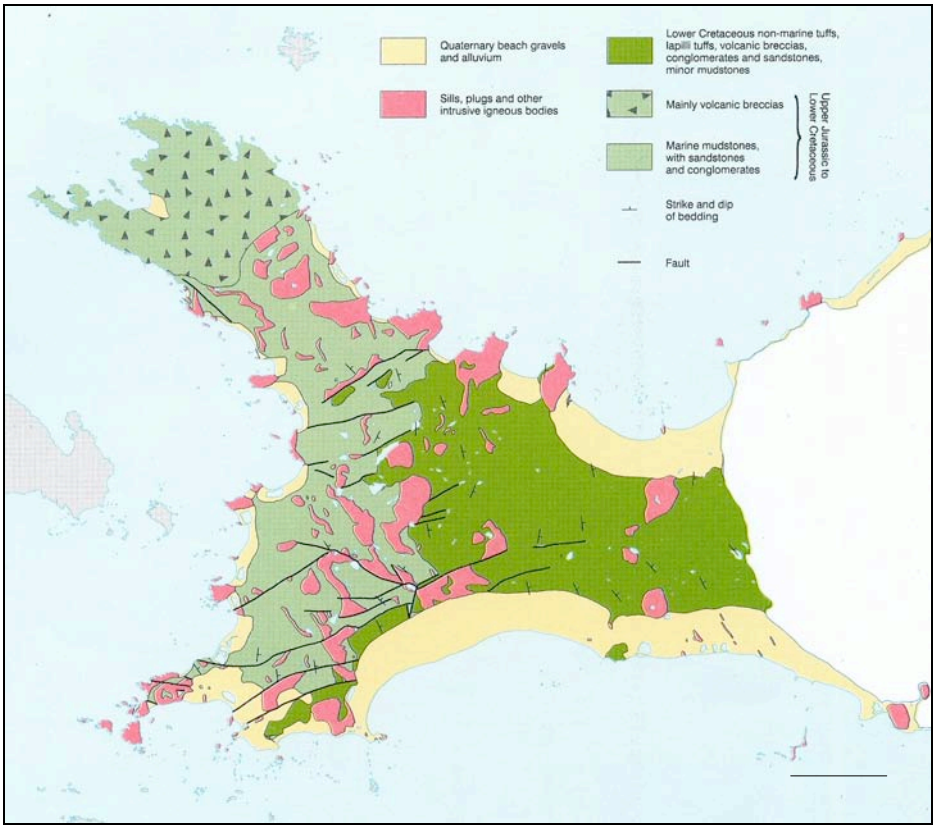

Figure 2.3. Geology of Byers Peninsula. Scale bar represents 2 km. (López-Martínez *et al.*, 1996a).

The predominant geology of Byers Peninsula involves highly friable rocks that form weakly lithified units, in which periglacial conditions promote shattering of the bedrock resulting in areas of debris that are generally in situ, but which have the potential to be transported locally (López-Martínez *et al.*, 1996a).

2.4 Geomorphology

With relatively little high ground and only residual glaciers remaining, there is good exposure of geomorphological features on Byers Peninsula. All pre-Holocene surfaces of Byers Peninsula display an obvious glacial landscape with the Rotch Dome ice cap representing the principal ice mass that has influenced the morphology of the peninsula. However, the general morphology is strongly dependent upon bedrock lithology and geological structures that may promote shattering of bedrock due to periglacial conditions (Martínez de Pisón *et al*., 1996).

Topographic highs include the volcanic plugs of Cerro Negro and Chester Cone, with the latter being the highest point on the peninsula with an elevation of 193 m (Martínez de Pisón *et al*., 1996). The peninsula is dominated by a series of extensive platforms, with altitudes of up to 105 m (a.s.l.) The coasts are occupied by contemporary and Holocene raised beaches with a total length of 71 km. The coasts generally have low relief with the exception of the northwest and in the few places where there are headlands (Martínez de Pisón *et al*., 1996).

2.5 Climate and drainage systems of Byers Peninsula

The climatic conditions on Byers Peninsula are maritime with meteorological records at Juan Carlos I Station (Hurd Peninsula, Livingston Island, Fig. 2.1) indicating mean annual temperatures below 0 °C, mean summer temperatures just above 0 °C, and an annual precipitation rate of 800 mm. As a result of these conditions, Byers Peninsula is snow-covered for the majority of the year, but is almost completely snow-free near the end of summer (López-Martínez *et al.*, 1996b).

Meltwater from snow, Rotch Dome and the three small glaciers, and a high annual precipitation rate results in the presence of considerable surface water during the summer months. Flat lying areas of the peninsula favour the retention of this surface water giving rise to temporary waterlogged areas, lakes and pools. Once these systems have become saturated, the excess surface water flows through a multi-channel drainage basin (López-Martínez *et al*., 1996b).

Byers Peninsula can be divided into three major drainage basins separated by local divides (Fig. 2.4): north basin 20.3 km^2 (covering 33.5% of the peninsula, A in Fig. 2.4); west basin 20.3 km^2 (33.5% of peninsula, B); and the south basin 18.9 km^2 (31% of peninsula, C), with a small area of undefined drainage. Drainage is to the north, west and south coasts respectively (López-Martínez *et al*., 1996b).

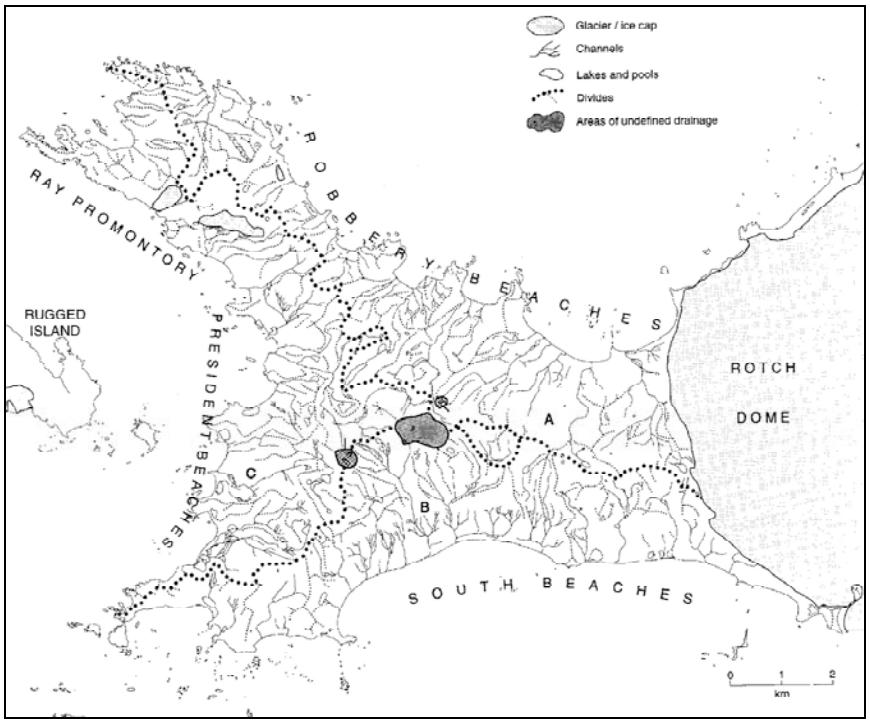

Figure 2.4. Drainage system of Byers Peninsula, letters referred to in text (López-Martínez *et al*., 1996b).

2.6 Characteristics of lakes of Byers Peninsula

Over 110 lakes and pools (with the definition that a lake will not freeze to the bottom whereas a pool will completely freeze over winter), covering an area of 0.92 km^2, are located on Byers Peninsula with their origins influenced by extensive terraced areas

and cirques. The majority of the lakes within this region is relatively recent in origin, and are a result of glacial over-deepening of tectonically controlled sites leading to generally shallow sub-circular to elongate basins influenced by fractures (Lopez-Martinez *et al*., 1996b).

Lakes near the coast that lie in shallow depressions are influenced by the sea, resulting in brackish lake water, whilst others at the higher central plateau are predominately freshwater due to substantial meltwater flow. These freshwater lakes are frozen to a depth of 1.0-1.5 m for 9-11 months of the year, have low sedimentation rates, low nutrient levels, are shallow (usually <5 m in depth) and contain highly transparent water (Ellis-Evans, 1996a).

The lake waters are predominately rich in silicate due to high weathering rates of alkaline volcanics and substantial tephra layers within the lake. Nitrate and phosphate levels are low and can be attributed to benthic algal mats stripping these inorganic nutrients (Ellis-Evans, 1996a). Organic nitrogen is high in most lakes and may be associated with nitrogen release from cyanobacterial mats throughout the catchment (Ellis-Evans, 1996a).

2.7 Biota of freshwater Antarctic Peninsula lakes

Antarctic freshwater lakes are characterised by short food chains that may be regarded as two level systems comprising of primary producers and crustacean grazers (Fig. 2.5) (Ellis-Evans, 1996b; Mataloni *et al*., 2000). These lake communities are strongly controlled by nutrient levels, ice-cover and ultraviolet light penetration through ice-cover and the water column (Jones *et al*., 1993; Ellis-Evans 1996a; Mataloni *et al*., 2000).

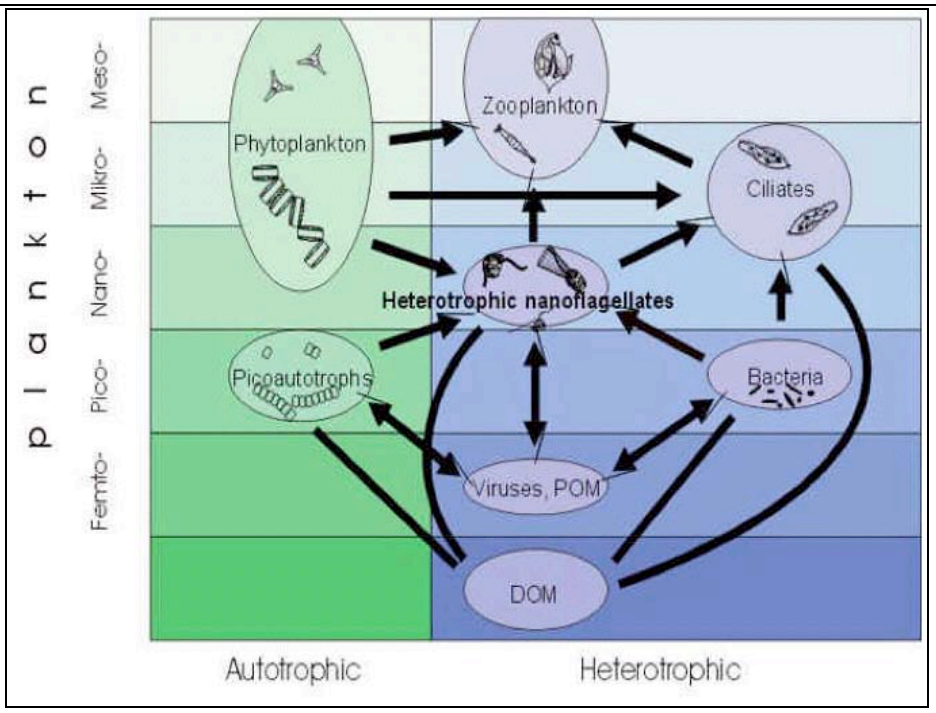

Figure 2.5. Typical food web for freshwater maritime Antarctic lakes (Camacho *et al.*, 2003b).

Algae and cyanobacteria are the main components of benthic freshwater communities, producing microbial mats, a characteristic of many Antarctic aquatic habitats (Vinocur and Pizarro, 2000). These algal mats dominate the biological productivity of the lakes and account for most of the lake's total biomass. They can occur in a wide range of morphologies and colour depending on the dominant forming species and the pigment production of those microorganisms. Aquatic mosses can also occur within Antarctic lake communities (Camacho and Fernández-Valiente, 2004).

Micro-invertebrates graze on the surface sediment and on the microbial mats. This community consists predominantly of tardigrades (*Dactylobiotus* cf. *ambiguus*; *Acutuncus antarcticus*), nematodes, rotifers (*Notholca* sp.), protozoa, a small number of cladocera (*Macrothrix* sp.) and ostracods, Branchiopods (*Branchinecta gainii*) and copepods (*Boeckella poppei*) (Ellis-Evans, 1996b).

2.8 Limnopolar Lake, Byers Peninsula

Lake sediments examined during this study were obtained from Limnopolar Lake on Byers Peninsula (62°40'S, 61°00'W), Livingston Island (South Shetland Islands). Limnopolar Lake (identified as Lake 4 within the supplementary notes for the geomorphological map of Byers Peninsula) can be seen in Figure 2.6, with the numbers on the map referring to individual lakes. The lake is 212 m in length, 125 m in width, has a total area of 19.4 ha and a maximum depth of 5.5 m (Fig. 2.7) (Jones *et al*., 1993; Thomson and Lopez-Martinez, 1996). A photo of Limnopolar Lake and its surrounding geomorphology is shown in Figure 2.8. Below is a list of organisms identified in Limnopolar Lake (Rico *et al*., 2003):

- The cladoceran *Macrothrix* sp.
- The copepod *Boeckella poppei*
- The chironomid *Parochlus steinenii*
- Unidentified Oligochaeta
- The bottom of the lake is covered by an extensive carpet of the moss *Drepanocladus*

Furthermore, other species undoubtedly occur within Limnopolar Lake.

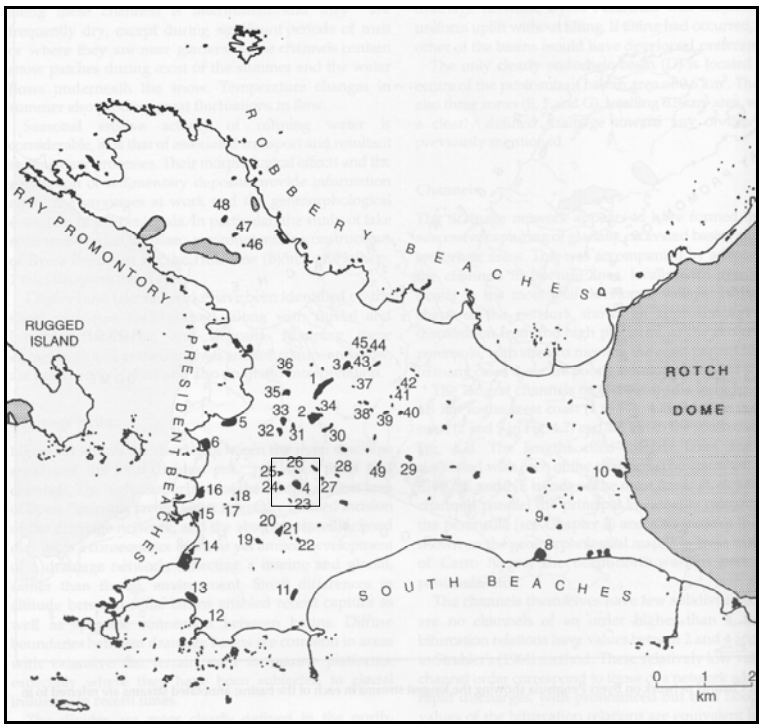

Figure 2.6. Map of lakes on Byers Peninsula, Livingston Island. Limnopolar Lake (Lake 4) highlighted by the box (Thomson and Lopez-Martinez, 1996).

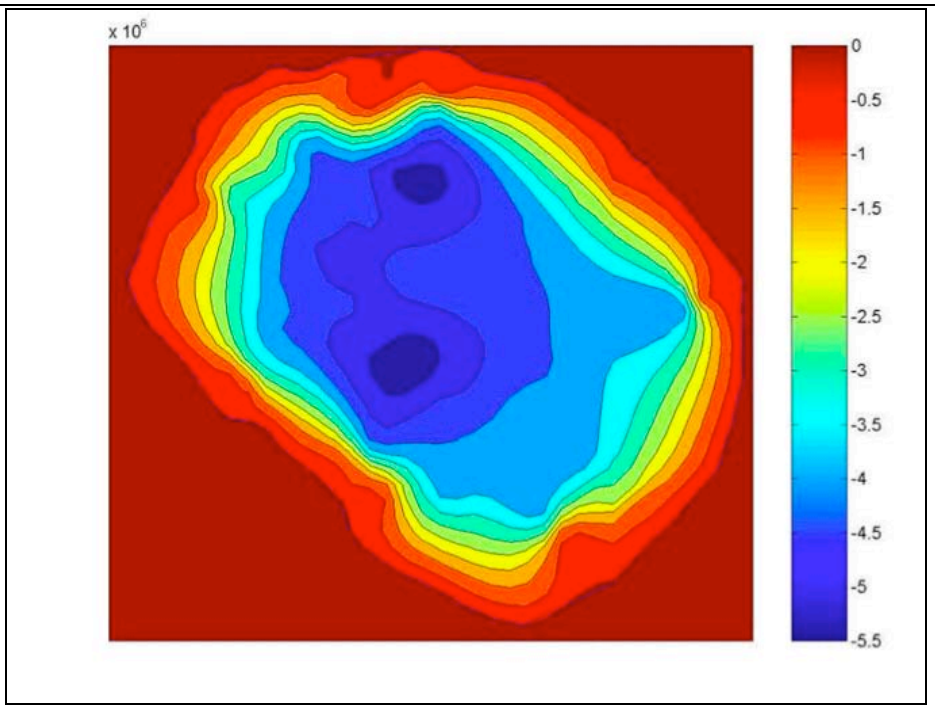

Figure 2.7. Bathymetry of Limnopolar Lake, Byers Peninsula (Camacho *et al.*, 2003b).

Figure 2.8. Photo of Limnopolar Lake (indicated by red arrow) and its surrounding geomorphology (Quesada, 2004).

Chapter Three

PHYSICAL BACKGROUND

3 Introduction

This chapter will focus on tephra, providing explanations of its nature, how it is formed, and its subsequent transportation and deposition into the ice and sediment records. A detailed analysis of tephrochronology and tephrostratigraphy studies is provided with an emphasis on the Antarctic region. This chapter also provides an outline of physical characterisation of sediment cores, including the percentage of organic carbon and carbonate of the sediment, and radiocarbon dating. These parameters give insights into various lake conditions such as sediment mineral loadings, sedimentation rates, lake water chemistry, and biological activity over time.

3.1 Tephra

Pyroclasts are predominantly solid fragments ejected into the air during an explosive volcanic eruption. Unlithified deposits composed of pyroclasts are known as tephra (Kyle *et al.*, 1982; Christopherson, 2000; Skinner and Porter, 1995; Summerfield, 1997; Wulf *et al*., 2002). Tephra can be categorised into three different groups on the basis of pyroclast size: volcanic ash consisting of particles less than 2 mm across; lapilli consisting of grains from 2-64 mm across; and the coarsest pyroclasts are known as volcanic bombs, if fluidly shaped, and blocks if angular in shape, measuring greater than 64 mm along the largest axis (Turney and Lowe, 2001).

Volcanic glass shards are fragments derived from silicate melt that has cooled and solidified during the eruption process. The shards are hard (approximately 5 on Mohs

scale of hardness), not readily soluble in water, extremely abrasive, mildly corrosive, and conduct electricity when wet (Ash Web Team USGS, 2005). Glass shards are commonly the principal pyroclast type in tephra of ash grain size.

The composition and chemical classification of tephra particles are strongly influenced by the composition of the magma from which they were derived. The composition of magma is controlled by the most abundant elements in the Earth: silicon; aluminium; iron; calcium; magnesium; sodium; potassium; and oxygen. As oxygen is the most abundant anion, oxides are used to express compositional variation of magmas. Silica (SiO_2) is the most abundant oxide in most magma types (Skinner and Porter, 1995). The compositions of magmas are largely differentiated into four main groups: basalt; andesite; dacite; and rhyolite, on the basis of silica content (Table 3.1). Andesite is often sub-divided into basaltic andesite from 51-57 wt% and "true" andesite from 57-63 wt% (Summerfield, 1997).

Table 3.1. Composition of magma on the basis of silica content (percentage by weight) (Skinner and Porter, 1995).

	Basalt (mafic)	Andesite (intermediate)	Dacite (silicic/felsic)	Rhyolite (silicic/felsic)
SiO_2	48-52%	52-63%	63-68%	>68%
FeO	10-12%	7%	5%	2.50%
MgO	6-10%	3%	2%	~1%
Na_2O	3%	3.50%	3.50%	3.50%
K_2O	1%	1.50%	2.00%	4.30%

3.2 Transport and deposition of tephra

During an explosive eruption, magma rises up the conduit and, on approaching the surface, rapid decompression occurs, causing volcanic gases to exsolve and expand. Rapidly expanding gas can disrupt the magma, and when released, results in a buoyant turbulent cloud of hot gases and tephra, known as an eruption column, being accelerated into the atmosphere. When equilibrium between the buoyancy of the ejected material and atmospheric pressure is established, the eruption column will spread laterally in the direction of prevailing winds (Fiacco *et al.*, 1993; Skinner and Porter, 1995). The distribution of tephra is dependent on the size of the eruption, the

abundance of pyroclasts ejected, and the direction and strength of prevailing winds in the atmosphere during a volcanic eruption (Turney and Lowe, 2001).

When the terminal velocities of the pyroclasts exceed the upward velocity in the eruption column, pyroclasts fall out, predominately downwind from the volcanic source (Summerfield, 1997; Turney and Lowe, 2001). Well-sorted, fining upward deposits are created as heavier particles are deposited first (Pyle, 1989; Sparks et al., 1992). Lighter ash particles can be dispersed thousands of kilometres from the volcanic source, and in very large volcanic eruptions, where fine particles can reach the stratosphere, such as Mount St Helens in 1980 and Mt Pinatubo in 1991, ash particles can encircle the globe before being deposited (Skinner and Porter, 1995; Summerfield, 1997; de Silva, 1998; Topinka, 2002).

The deposition of coarse tephra will predominantly occur within hours to days following an explosive eruption. Finer ash particles settle out over a period of months to even years (Turney and Lowe, 2001). Therefore, in geological terms, tephra horizons can be regarded as instantaneous time-parallel horizons (Turney and Lowe, 2001; Hunt and Hill, 1993).

3.3 Morphology of volcanic ash

Volcanic glass shards are isotropic (have the same optical properties in all directions) under cross-polarised light and display varying degrees of vesicularity (small spherical or ellipsoidal cavities found in volcanic rocks, which are produced by trapped gas bubbles during the solidification of the rock). The morphology of glass shards is dependent on the composition, temperature, and volatile content of the magma, as these factors control viscosity and surface tension. Therefore, the shape of glass shards can be used to interpret the type of volcanic eruption from which they were derived, and may also indicate the degree of magma/water interaction (Heiken and Wohletz, 1992).

However, shard morphology alone is rarely sufficient to distinguish deposits from single eruptions, as diverse morphologies may occur in tephra horizons derived from

a single volcanic centre, and different eruption centres that have similar lithological compositions may produce similar morphologies. It is therefore imperative that chemical analysis be carried out on the shards to aid in this identification process (Turney and Lowe, 2001).

Shard morphologies documented from Livingston Island tend to be dominated by blocky, moderately vesicular (Fig. 3.1a) to non-vesicular (Fig. 3.1b) grains. Non-vesicular glass shards are commonly produced by phreatomagmatic eruptions in which explosions are driven by steam generation when magma and external water interact.

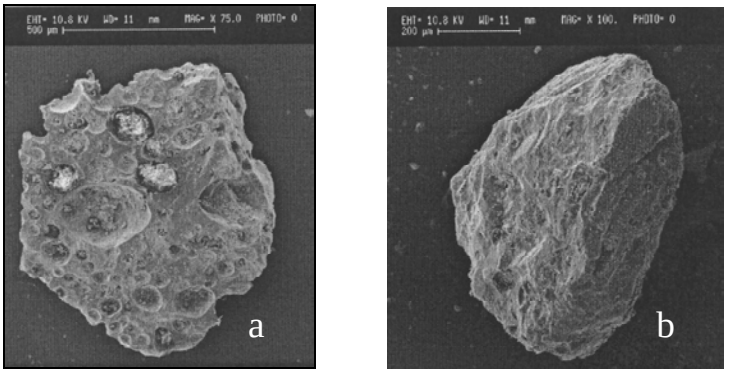

Figure 3.1. a) Moderately vesicular, blocky shard from Livingston Island (Pallàs *et al*., 2001) and b) Non-vesicular blocky shard from Livingston Island (Pallàs *et al*., 2001).

3.4 Tephrochronology and tephrostratigraphy

Volcanoes are globally widespread, although most volcanic eruptions occur where tectonic plates collide. The subduction of oceanic plates underneath thicker continental plates leads to the evolution of a line of volcanoes known as a volcanic arc (Simkin *et al.*, 1981; Summerfield, 1997). This volcano-forming process is continually taking place across the globe, as tectonic plates are constantly in motion. Throughout geologic time, explosive volcanic eruptions have generated tephra deposits. Monitoring of tephra deposition across the world is the basis of tephrochronology (dating of various tephra horizons) and tephrostratigraphy (stratigraphic correlations of tephra within sediment or ice cores) (Turney and Lowe, 2001).

Distinctive tephra deposits provide widespread isochronous markers that allow accurate dating of environmental and climatic events, and precise correlations between ice cores and marine and terrestrial sedimentary sequences across large areas (Kyle *et al*., 1982; Turney and Lowe, 2001; Beierle and Bond, 2002; Wulf *et al*., 2002; Hall and Alloway, 2004). As a result, tephrochronology and tephrostratigraphy are invaluable tools that may be used to establish accurate chronologies in regions where radiocarbon dating is unreliable (Björck *et al*., 1991d).

Tephrostratigraphy is reliable only for single tephra layers that can be uniquely identified from their chemical and physical characteristics. This reduces the possibility of invalid correlations with tephra layers that may have similar chemical signatures or physical morphologies (Hunt and Hill, 1993; Moreton and Smellie, 1998; Turner and Lowe, 2001; Beierle and Bond, 2002).

As glass shards are predominantly homogeneous quenched pyroclasts that display little or no crystallisation of mineral phases, their composition should not vary with distance from the volcanic source. The composition of tephra layers consisting of glass shards is representative of the melt part of the parent magma and is uniquely characterised by major and minor element components (Dugmore *et al*., 1992). Due to this fact, geochemical analysis, such as electron probe microanalysis (EPMA), not only aids in the identification of tephra horizons and correlation between horizons, but can also be utilised to determine the parent volcanoes (Hodgson *et al*., 1998; Lowe and Turney, 2001).

3.5 Possible Holocene volcanic sources of tephra

Volcanoes have only been identified in the sub-Antarctic and Antarctic region within the last 200 years. The sub-Antarctic Islands were some of the first volcanoes to be discovered by sealers, whalers and explorers (LeMasurier, 1990). On January 27, 1841, Sir James Ross discovered Mount Erebus. It was described as ″emitting flame and smoke in great profusion″ and on January 28, 1841, ″some of the officers believed that they could see streams of lava pouring down the sides until lost beneath the snow″ (Ross, 1847; Kyle, 1990).

Volcanoes within the Antarctic can be divided into seven groups: McMurdo Volcanic Group - Western Ross Embayment; Marie Byrd Land; Alexander Island, Palmer Land, and Ellsworth Land; Graham Land and South Shetland Islands; South Sandwich Islands; oceanic islands on the Antarctic Plate; and subantarctic volcanoes of the Pacific Plate (Fig. 3.2) (LeMasurier, 1990).

Tephra horizons found on Byers Peninsula (located in section D of Fig. 3.2) are most likely to have volcanic sources from the South Shetland Islands, Graham Land, or from the South Sandwich Islands due to their close proximity. Eruptions from more distant volcanic sources around the Antarctic, or other regions of the globe, could also deposit tephra on Byers Peninsula, providing that a large volume of material is ejected into the stratosphere and that atmospheric circulation patterns are sufficient to transport pyroclasts from the eruptive column to the region.

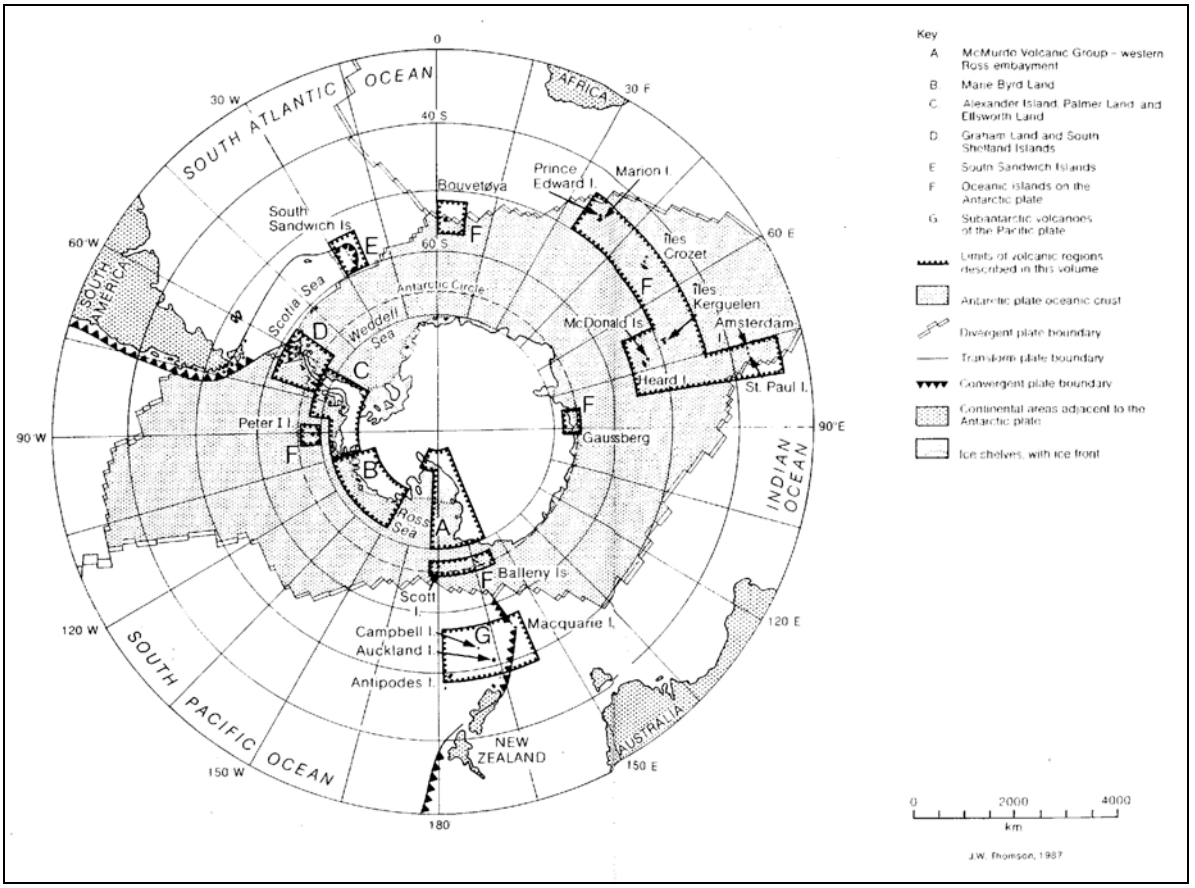

Figure 3.2. Map of Antarctica displaying the seven volcanic groups (Thomson, 1987).

3.5.1 Graham Land and South Shetland Islands

Graham Land and the South Shetland Islands (Fig. 3.3) unusual environments as they contain diverse tectonic settings including the formation of volcanic arcs, back-arcs, and within-plate volcanoes, in a small geographical area. The result is a wide variety of magma types within this region - volcanic arcs producing calc-alkaline magmas, within-plate volcanoes creating alkaline magmas, and transitional magmas displaying a variety of arc, mid-ocean ridge, and within-plate geochemical characteristics (Smellie, 1990). Recent eruptions on Deception Island, Bridgeman Island, and Penguin Island, and hydrothermal activity on King George Island, suggest that volcanism related to plate extension is still taking place within this region (Matthies *et al.*, 1988; Smellie, 1990).

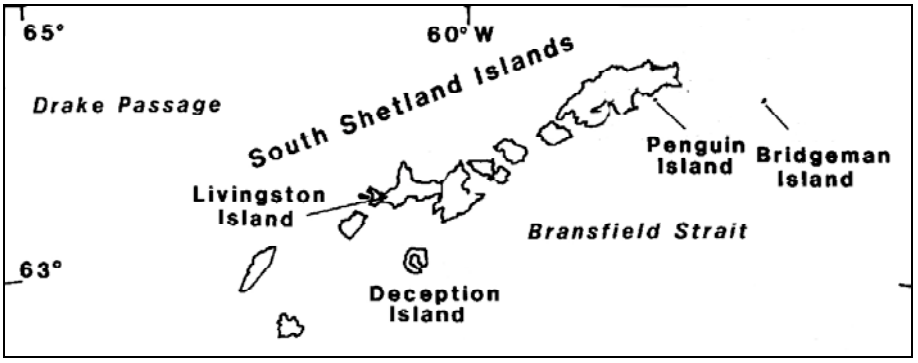

Figure 3.3. Map of the South Shetland Islands, highlighting Livingston Island, Deception Island, Penguin Island, and Bridgeman Island. Arrow pointing to Livingston Island also lies on Byers Peninsula (Smellie, 1990).

Bridgeman Island: Bridgeman Island is a remnant stratovolcano located in the Bransfield Strait (62°03′S, 56°45′W). The lavas from this region are high-alumina basaltic andesites that were predominantly generated during initial stages of back-arc spreading (Smellie, 1986a). There have been numerous records of fumarolic activity between 1821 and 1880 from Bridgeman Island; however, the region appears to have been inactive since 1909 (Adie, 1957).

Penguin Island: A small stratovolcano located at 62°06′S, 57°56′W, producing slightly under-saturated alkali basalts. Some of the Holocene volcanic reports relating to Bridgeman Island have been attributed to Penguin Island as fresh volcanic cones are preserved only on Penguin Island (Smellie, 1986b).

Deception Island: Deception Island is a caldera located in the Bransfield Strait (63°00′S, 60°40′W). It is the largest and most active volcano in the Antarctic Peninsula region and has been identified as the most likely source of tephra horizons found in the South Shetland Islands, South Orkney Islands, and the Scotia Sea (Smellie, 1999; Björck *et al.*, 1991a; Smellie, 2001; Fretzdorff and Smellie, 2002). Lavas from this locality include olivine and quartz tholeiites, basaltic andesites, and dacites. The basalts from Deception Island have a distinctive geochemical signature and can be divided into high-iron and high-alumina groups (Baker, 1985). These geochemical characteristics are a result of Deception Island being located on a supra-subduction zone spreading centre within an active marginal basin (Weaver *et al.*, 1979).

The first historical report of Deception Island eruptions was by Wilkes in 1845, reporting "The whole south side of Deception Island appeared as if on fire". On the inspection of windblown dust layers in the ice, it has been suggested that a series of explosive eruptions occurred during 1912-1917. In December 1967, three new craters produced an island in Telefon Bay. Additional eruptions occurred from a crater on the north-northeast side of Port Foster (Baker, 1985; Smellie, 2001; Rey *et al.*, 2002). In 1967, a number of craters erupted near Mount Pond destroying the Chilean Scientific Station at Pendulum Cove and severely damaging the British Station at Whalers Bay (Baker, 1985; Smellie, 2001). In August 1970, there was additional activity in Telefon Bay with a new chain of craters being developed (Fig. 3.4) (Baker, 1985; Pallàs *et al.*, 2001).

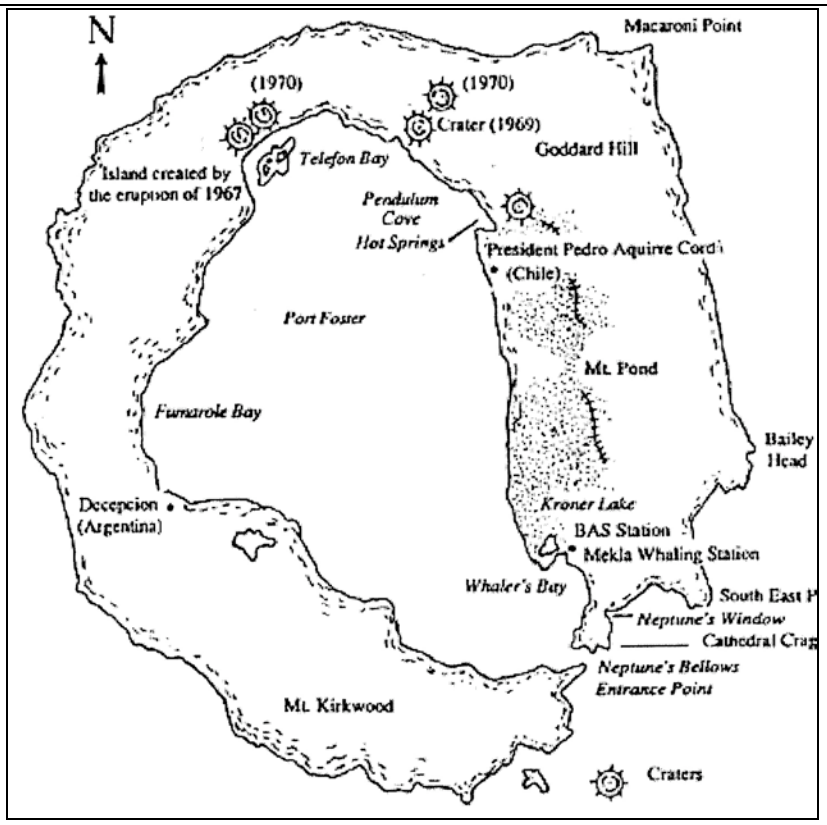

Figure 3.4. Map of Deception Island, showing locations of eruptions (LaFara, 1996).

3.5.2 South Sandwich Islands

The South Sandwich Islands (56°18′-59°28′S, 26°14′-28°11′W) (Fig. 3.5) are part of a young and small island arc extending over a distance of 350 km along the eastern margin of the Scotia Sea (Baker, 1990). Stratovolcanoes and parasitic cones are the dominant volcanic landforms in this region. Basalt is the dominant rock-type, with 60% of its volume in lava and 40% by tephra (Baker, 1990). Although the South Sandwich Islands are rarely visited, historic and/or fumarolic activity has been observed on 8 of the 11 islands (Baker, 1990). Volcanic centres with evidence of Holocene activity are listed in Table 3.2.

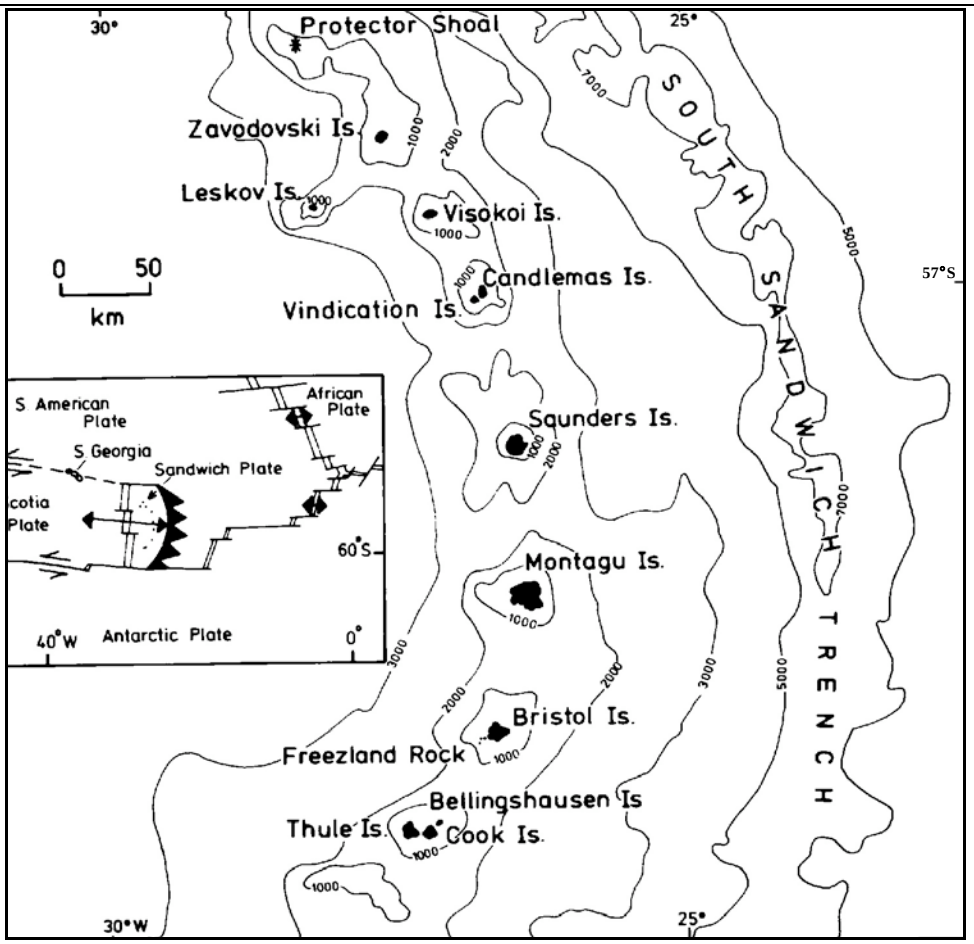

Figure 3.5. Map of the South Sandwich Islands, inset plate shows plate boundaries and motions of this location (Baker, 1990).

Table 3.2. Volcanoes with Holocene activity from the South Sandwich Islands (data extracted from Baker, 1990).

Name	Location	Volcano Type	Lava Composition	Holocene Activity	Reference
Mount Curry, Zavodovski Island	56°98'S, 27°34'W	Stratovolcano	Basalt	Numerous fumarolic activities in summit crater since 1819. Sulfurous vapour reported in 1964. Fresh lava reported in 1830.	Baker, 1986a.
Protector Shoal	55°55'S, 28°05'W	Seamount	Dacite	Earthquake on March 5, 1962 and extensive pumice raft discovered on March 14, 1962.	Baker, 1988; Gass *et al.*, 1963.
Mount Hodson, Visokoi Island	56°42'S, 27°09'W	Stratovolcano	Basalt-andesite	Captain J. Brown referred to Visokoi Island as "a burning mountain with smoke issuing from it in several places" in 1830. A plume was also observed in 1930.	Baker, 1986b; Kemp and Nelson, 1931.
Candlemas Island	57°05'S, 26°43'W	Stratovolcano with attached scoria cones and lava flows	Basalt-andesite and dacite	Steam emission, geysers, and hot pools have been observed on several locations over the last 100 years.	Baker, 1986c.
Mount Michael, Saunders Island	57°47'S, 26°27'W	Stratovolcano with lava platform and parasitic cones	Basalt-andesite	Numerous reports of vapour emissions from the summit crater since 1820	Baker, 1986d.
Bristol Island	59°02'S, 26°35'W	Stratovolcano	Basalt-andesite	In 1962 a steaming crater was observed. In 1964 remnant cinders on ice were discovered and eruptions witnessed in 1935 and 1956.	Baker, 1986e; Holdgate and Baker, 1979.
Bellingshausen Island	59°26'S, 27°05'W	Small stratovolcano	Andesite	Persistent and extensive fumarolic activity around crater rim.	Baker, 1986f.
Thule Island	59°27'S, 27°22'W	Stratovolcano	Basalt-andesite	In 1962 steam reportedly rising from crater and ash observed on surface of ice.	Baker, 1986g; Holdgate and Baker, 1979.

3.6 Tephrochronology and tephrostratigraphy in the Antarctic

Tephra layers are widespread in Antarctic lake sediments and ice due to the large number of Quaternary eruptions from Antarctic volcanic centres, and as a result of the ease of volcanic ash transportation and deposition in this region (Koeberl, 1989; Smellie, 1999; Narcisi *et al*., 2001). Global wind circulation patterns ensure that large volcanic eruptions within the Southern Hemisphere, and up to 20°N, have good potential for forming tephra layers in Antarctic sediment and ice stratigraphy (Delmas *et al*., 1985; Smellie, 1999). As the tropopause above Antarctica is usually low, between 8-10 km, even small eruptions within the Antarctic region have the potential for eruption columns to reach the stratosphere, resulting in rapid and widespread deposition of tephra (Kyle *et al*., 1981; Smellie, 1999).

Tephra studies within the Antarctic have predominantly been based on ash layers within ice cores and blue ice areas (Table 3.3; Fig 3.6). However, the study of tephra horizons in sub-lacustrine and marine settings has been largely neglected. As a result, chemical data on glass shards are not uniformly available across the Antarctic, especially in the Antarctic Peninsula where chemical analyses have only been published within the last 6 years (Smellie, 1999).

Tephra studies on the Antarctic Peninsula date back to 1972, as a result of heightened interest following a series of eruptions from Deception Island between 1967 and 1970. Existing named tephra layers in this region are poorly described and as a result, multiple tephra layers are virtually impossible to differentiate due to insufficient data on distinguishing characteristics (Smellie, 1999). Additionally, few tephra shards have been dated directly, although potassic glass and various minerals commonly present in tephra can be readily prepared for isotopic dating (Smellie, 1999).

Table 3.3. Identified Holocene tephra horizons on Continental Antarctica, localities identified in this table are shown in Fig 3.6 (modified from Smellie, 1999).

Location	Lithologies	Source	Age estimate	Reference
Lewis Cliff	Basanite, K-trachyte	Pleiades, south Victoria Land	Unknown (Holocene)	Koeberl *et al*., 1988; Koeberl, 1989.
Byrd ice core	Per-alkaline trachyte	Mt Takahe, Marie Byrd Land	7.5-43.5 ka	Gow *et al*., 1968; Gow and Williamson, 1971.
South Pole ice and firn cores	Andesite	Cosequina	1835 ± 5 AD	King and Wagstaff, 1980; Kyle *et al*., 1982; Palais *et al*., 1987, 1989b, 1990, 1992; Delmas *et al*., 1992.
Vostok ice cores	Tholeiitic andesite	South Sandwich Islands	3.2 ka	Kyle *et al*., 1981, 1984; Palais *et al*., 1987, 1989a.
EPICA - Dome C ice core	Alkalic-tholeiitic	South Shetland Islands	3.5 ka	Narcisi *et al*., 2005.
Mount Waesche, Marie Byrd Land	Basalt, phonotephrite	Mt Waesche and unknown	Unknown (Holocene)	McIntosh *et al*., 1990; Smellie *et al*., 1990 and unpublished.

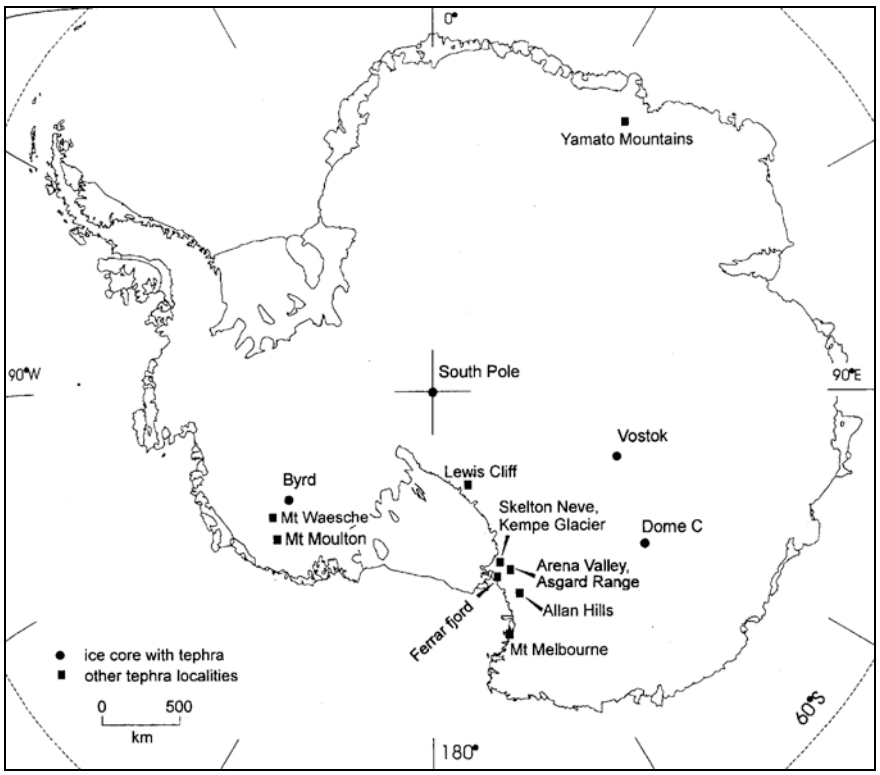

Figure 3.6. Map of the Antarctic continent, displaying the locations of tephra as described in Table 3.3 (Smellie, 1999).

Previous studies of tephra horizons from Lake Åsa, Chester Cone Lake and Midge Lake (Livingston Island) (Björck *et al*., 1991c; Hodgson *et al*., 1998), Sombre Lake (Signy Island) (Hodgson *et al*., 1998), Hidden Lake (James Ross Island), Lake Boeckella (Hope Bay), and Walker Point (Elephant Island) (Björck *et al*., 1991a; 1991c; Björck and Zale, 1996) together with radiocarbon dating of moss remains in the area has led to the construction of a preliminary tephrochronology for the northern Antarctic Peninsula (Table 3.4; Fig 3.7) (Hodgson *et al*., 1998).

Table 3.4. Identified Holocene tephra horizons from the northern Antarctic Peninsula localities identified in this table are shown in Fig 3.8 (modified from Smellie, 1999).

Location	Lithologies	Source	Age estimate	Reference
Livingston Island	Basaltic andesite to dacite	Deception Island	4700, 2650-2750, 2500, 1350, 1250-1400, 750-800, 450 yrs BP	Björck *et al*., 1991a,b, 1993; Björck and Zale, 1996; Hodgson *et al*., 1998.
James Ross Island	Unknown	Deception Island	2500, 2100, 1850, 1050, 750, 450, 250 yrs BP	Björck *et al*., 1991c.
Hope Bay, Graham Land	Basaltic andesite	Deception Island	4700, 2500, 2100, 1850, 1350, 1050, 450 yrs BP	Björck *et al*., 1991c.
Elephant Island	Unknown	Deception Island	5000?, 4100?, 3500, 2500, 2250, 2100, 1850 yrs BP	Björck *et al*., 1991b,c.
King George Island	Unknown	Penguin Island?	5200-3800 yrs BP	Tatur *et al*., 1991.
South Orkney Island	Basaltic andesite	Deception Island	30 ± 4 BP - 125 ± 25 yrs BP, 1325 ± 50 ^{14}C BP, 1021 ^{14}C BP, 1450 ^{14}C BP	Hodgson *et al*., 1998.
Bransfield Basin	Basalt to andesite	Deception Island	1839-42, pre 1829, 1967, 1970	Fretzdorff and Smellie, 2002.
James Ross Island	Basaltic andesite	Deception Island	2 AD	Palais *et al*., 1989b; Aristarain and Delmas, 1998
Deception Island, Mt Pond Ice Cap	Basalt to andesite	Deception Island	1931-1955	Roobol, 1973; Pallàs *et al*., 2001

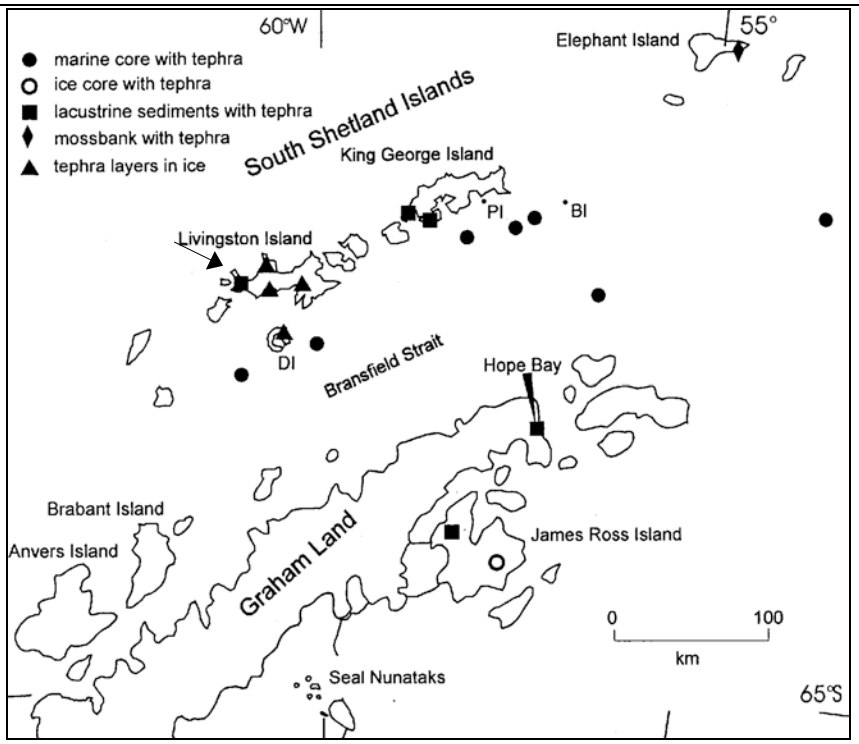

Figure 3.7. Map of the Antarctic Peninsula, displaying tephra locations as described in Table 3.4. Abbreviations: PI = Penguin Island; BI = Bridgeman Island; DI = Deception Island. Arrow indicates location of Byers Peninsula on Livingston Island (Smellie, 1999).

3.7 Tephra composition and correlation

The identification and geochemical analysis of tephra horizons enable single horizons to be correlated to a possible volcanic source and comparisons to be made with other local tephra horizons. This process can be carried out in two ways: comparisons with previously identified tephra horizons and through the use of bulk volcanic rock compositions (Hodgson *et al*., 1998; Moreton and Smellie, 1998; Pallàs *et al*., 2001; Fretzdorff and Smellie, 2002).

Bulk volcanic rock analyses are an excellent method of determining possible volcanic sources, because tephra compositions are strongly dependent on parent magma composition (Turney and Lowe, 2001). For example, bulk volcanic rock analyses of the South Shetland Islands and Graham Land can be presented graphically (Fig. 3.8). The geochemical analyses of tephra shards can also be shown on this same plot. Shards with compositions that do not lie in close proximity to the bulk volcanic rock analyses were probably not sourced from those volcanic centres.

Tephra shards that have compositions similar to the bulk volcanic rock composition may be interpreted as the products of that volcanic centre (Pallàs *et al.*, 2001).

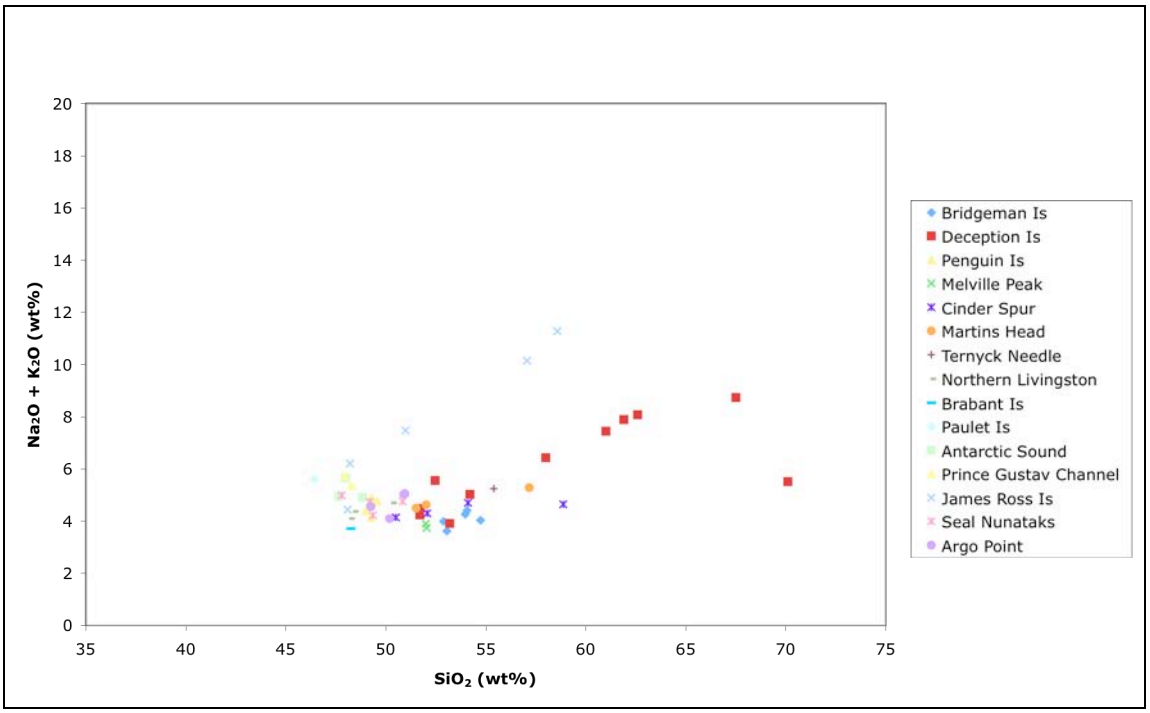

Figure 3.8. Example of geochemical plot of bulk volcanic rock analyses from the South Shetland Islands and Graham Land (LeMasurier and Thomson, 1990).

3.8 Tephra summary

Pyroclasts ejected from explosive volcanic eruptions have the potential to be transported and deposited in a wide range of continental and marine settings. Due to problems with radiocarbon dating on the Antarctic Peninsula, tephrochronology has become an important tool for dating and correlating stratigraphic records. Volcanic sources for tephra horizons can be established through geochemical and morphological analyses of pyroclasts. A preliminary tephrostratigraphy for the Antarctic Peninsula has been established. Deception Island has been identified as the most likely source of tephra for this region. However, the tephra record is presently scattered, incomplete and poorly described, resulting in correlations among multiple tephra horizons being virtually impossible. Therefore, it is essential that additional tephra studies within the region be carried out to improve and strengthen the current tephrochronology of the region.

3.9 Organic and inorganic carbon in sediment

It is important to understand the organic and inorganic attributes of sediment cores as they may provide information on how tephra may be influencing the chemistry of lake water and productivity within the lake.

Despite carbon dioxide having a relatively small concentration within the atmosphere (~0.035%), it has high solubility in water, so that carbon and its compounds are important components of lake water chemistry. The carbon content of lake sediment cores has the potential to provide archives of organic and inorganic carbon fixation within the water column, which can be related to organic productivity within the lake (Cohen, 2003). Carbon can enter lake environments by two main methods: autochthonous (internal) dissolution of carbon dioxide and uptake through photosynthesis; and allochthonous (external) inputs derived from the physical breakdown and chemical decay of terrestrial organisms (Cohen, 2003). Upon dissolution in lake water, a small proportion of carbon dioxide hydrates to form carbonic acid (Equation 3.1):

$$H_2O + CO_2 \Leftrightarrow H_2CO_3 \quad (3.1)$$

The carbonic acid may undergo two further dissociations to form carbonate ions that can then be precipitated with Ca^{2+} to form $CaCO_3$ (Equation 3.2 and 3.3):

$$H_2CO_3 \Leftrightarrow H^+ + HCO_3^- \quad (3.2)$$

$$HCO_3^- \Leftrightarrow H^+ + CO_3^{-2} \downarrow_{CaCO_3} \quad (3.3)$$

$$Ca^{2+} + CO^{2-} \Leftrightarrow CaCO_3 \text{ (solid)} \quad (3.4)$$

Carbon occurs in various organic and inorganic forms in lakes, as both particulate and dissolved carbon, moving readily between these two states through the chemical reactions above and via the formation of organic carbon (Cohen, 2003). The largest reservoir of organic carbon in lakes is typically dissolved organic carbon (~90%); particulate organic carbon accounts for only 10% of the total organic carbon load. However, it is the particulate organic carbon that is the dominant source of organic matter within lake sediments (Dean, 1999; Cohen, 2003).

Organic matter constitutes an important fraction of lake sediments and originates from the complex mixture of lipids, carbohydrates, proteins, and other biochemicals produced by lake organisms. The organic matter content of the lake sediments, therefore, provides important information of lacustrine palaeoenvironments (Meyers and Lallier-Vergès, 1999). In general, increased organic carbon results in increased primary production.

Inorganic carbon, in the form of calcium carbonate, occurs in a number of different minerals (e.g., calcite and aragonite) (Morse and Mackenzie, 1990). Precipitation and dissolution of calcium carbonate in lake environments is an equilibrium relationship. Dissolution of calcium carbonate produces carbon dioxide until equilibrium is re-established. The subsequent removal of carbon dioxide reverses this reaction, resulting in a precipitation of calcium carbonate (Cohen, 2003).

Two main causes of calcium carbonate precipitation in lakes are photosynthesis and carbon dioxide degassing. However, an increase in lake productivity (increasing organic carbon production due to eutrophication) may in fact cause the dissolution of calcium carbonates through the addition of carbon dioxide during respiration and decomposition of organic matter (Dean, 1999; Cohen, 2003).

Sequential loss on ignition (LOI) is a simple and widely used technique for estimating the organic and carbonate content of sediments in palaeolimnological studies (Ball, 1964; Battarbee *et al*., 2002; Beaudoin, 2003). This method is based on differential thermal analysis, where plant matter dehydrates between 40-135 °C and begins to ignite at ~200 °C (Dean, 1974; Santisteban *et al*., 2004). Organic matter is completely oxidised between 500-550 °C to carbon dioxide and ash (Heiri *et al*., 2001). Inorganic minerals are destroyed at higher temperatures, dolomite between 700-750 °C, calcite between 800-850 °C. Carbon dioxide is evolved from most inorganic carbonates at 900-1000 °C, leaving metal oxides (Equation 3.5)(Heiri, *et al*., 2001; Santisteban *et al.,* 2004).

$$CaCO_3 \longrightarrow CaO + CO_2 \qquad (3.5)$$

Therefore, the organic carbon content and inorganic carbon content can easily be calculated through weight loss, determined by weighing samples before and after ignition and determining the weight percent loss by difference, producing empirical values. Additionally, inorganic carbon is multiplied by the molecular weight of calcium carbonate divided by the molecular weight of carbon dioxide, to account for the fact that heating to 950 °C only removes a defined fraction of the $CaCO_3$. Here I define $*LOI_{950}$ as loss on ignition at 950 °C corrected for this consideration (Equation 3.6) (Dean, 1974; Heiri *et al.*, 2001; Boyle, 2004).

$$\%*LOI_{950} = \left(\frac{M_{950} - M_{550}}{M_D}\right) X \left(\frac{mw_{(CaCO_3)}}{mw_{(CO_2)}}\right) X100 \qquad (3.6)$$

Where M = dry mass

M_{550} = mass after heating at 550 °C

M_{950} = mass after heating at 950 °C

mw = molecular weight

3.10 Radiocarbon dating

Radiometric dating uses radioactive (unstable) isotopes and their transformation into daughter isotopes, with the emission of various particles at known rates. Radiocarbon dating is the most important and widely used radiometric dating method in palaeolimnology studies (Zale, 1994a; Cohen, 2003).

Natural carbon has three isotopes, ^{12}C and ^{13}C (stable isotopes) and ^{14}C (unstable isotope). ^{14}C is produced by the interaction of cosmic rays with nitrogen and oxygen atoms in the upper atmosphere and undergoes β-decay to form ^{14}N with a half-life of 5,730 years. ^{14}C oxidises to $^{14}CO_2$, in which form it can be taken up by the biosphere (Trumbore, 2000).

The relatively rapid cycling of carbon between the atmosphere and the biosphere allows plants to maintain a ^{14}C level that is approximately equal to that of the

atmosphere. Upon the death of an organism, the ^{14}C in its tissues can no longer interact with the atmospheric carbon dioxide, and during decomposition undergoes radioactive decay back to ^{14}N. This decrease in ^{14}C content compared to that in living organisms is the basis of radiocarbon dating (Trumbore, 2000).

Caution should be used when applying radiocarbon dating. Errors can be caused by stratigraphical complications, contamination, the carbon reservoir effect, and through anthropogenic effects (Björck *et al.*, 1991b; Doran *et al.*, 1999; Trumbore, 2000; Emslie, 2001; Turney and Lowe, 2001; Cohen, 2003). Stratigraphic complications may arise where folds or thrust faults result in older units being emplaced on top of younger units. However, an understanding of the local geological structure can eliminate this as a source of error (Cohen, 2003). Contamination can occur, both within a lake environment through sources such as roots, and also through laboratory procedures. This is an important consideration as radiocarbon dating is an estimate of the age of the material being analysed, which may not be contemporaneous with the surrounding deposit (Cohen, 2003).

Since the mid-nineteenth century, the ^{14}C content of the atmosphere has been strongly influenced by anthropogenic effects. Since the beginning of the industrial revolution, large amounts of "old" carbon dioxide have been released into the atmosphere, causing the dilution of naturally occurring carbon dioxide. This effect has resulted in a decrease in the proportion of ^{14}C within the atmosphere. Conversely, the detonation of nuclear bombs since the early 1960s has dramatically increased the atmospheric content of ^{14}C (Björck *et al.*, 1991b; Berkman and Forman, 1996).

The carbon reservoir effect involves the slow overturning of ocean waters, producing waters that have been depleted in ^{14}C. It has been estimated that the ^{14}C in oceans is involved in this process for approximately 1000 years, although the duration varies with depth and is different in various oceans (Emslie, 2001; Roberts *et al.*, 2001). As a result, deep-sea water is, on average, 1000 years older, in terms of carbon, than the contemporaneous atmosphere. Reservoir effects can also occur when older carbon sources from bedrock geology or soils results in significant lowering of the initial $^{14}C/^{12}C$ ratio relative to the atmospheric ratio at the time of formation (Björck *et al.*, 1991b; Cohen, 2003).

Most of these problems have been encountered in radiometric dating of lake sediment cores from various islands around the Antarctic Peninsula. Björck *et al.* (1991a) carried out investigations on various lakes around the northern peninsula of Antarctica. Twenty ^{14}C dates were obtained, however, most of these sediment dates were prone to errors resulting in overestimates in the ^{14}C ages. Major ^{14}C dating problems have been encountered from lake sediment samples from Lake Boeckella, which have been attributed to the presence of old carbon in the bedrock and a large input of penguin guano from the adjacent penguin rookery (due to the marine reservoir effect) (Zale, 1994b).

Pallàs *et al*. (2001) stated that the study of temperate glaciers on the northern Antarctic Peninsula is strongly hampered by a lack of suitable dating techniques. Summer melting causes the glaciers to lose complete annual layers, thus disrupting the migration of stable isotopes. Therefore, dating these glaciers through conventional annual layer counting and radiometric techniques is not possible. It was concluded that this problem could be overcome through the use of regional tephrochronology (Pallàs *et al.*, 2001)

Additionally, mass spectrometry was carried out on a moss bank from Midge Lake, Livingston Island, providing a reliable ^{14}C date. However, by combining the radiocarbon dating from the moss bank, age/depth curves and the cross correlation of various tephra horizons, more accurate dating was obtained (Björck *et al*., 1991a).

Chapter Four

ECOLOGY BACKGROUND

4 Introduction

To comprehend ecosystem changes within a lake environment it is imperative to understand the biology and life histories of the organisms involved. Only then can assumptions be made concerning ecosystem changes driven by biological processes (e.g. predator-prey relationships) or environmental variables (e.g. climate, tephra input). Descriptions of common freshwater northern Antarctic lake organisms including morphology, certain aspects of biology, life histories, and documented distributions around the northern Antarctic Peninsula are included below. The preservation of the remains of these organisms is also discussed along with documented responses of common freshwater northern Antarctic lake organisms to tephra inputs into the lake environment.

4.1 Common northern Antarctic organisms found in freshwater lakes

4.1.1 Rotifers

Rotifers are Metazoa that are small, generally between 0.1-1 mm long, and exhibit a wide range of morphological variations and adaptations. In most, the body shape tends to be elongated, and regions of the head, trunk, and foot are usually distinguishable (Wetzel, 2001; Cohen, 2003; Brönmark and Hansson, 2005). Most rotifers are solitary, but some may form permanent colonies. Most are non-predatory, omnivorous filter feeders, by means of ciliary movement of living and detrital particulate organic matter into the mouth cavity. They consume bacteria, algae and

small ciliates (Wetzel, 2001; Brönmark and Hansson, 2005). The distinguishing characteristic of this phylum is a crown of cilia at the anterior end of the trunk; the distribution of these cilia crowns varies among the rotifer species (Dorit *et al*., 1991).

Rotifers play an important role in freshwater systems mainly because of their enormous reproductive potential resulting in large grazing pressures (Brönmark and Hansson, 2005). Rotifers are generally parthenogenetic, where the egg develops without fertilisation into a new individual identical to the mother. A sexual phase may follow where unfertilised females lay small eggs that hatch as dwarf males. Larger fertilised eggs are developed into thick-walled resting eggs (Fig. 4.1) (Everitt, 1981; Barnes *et al*., 1993; Brönmark and Hansson, 2005).

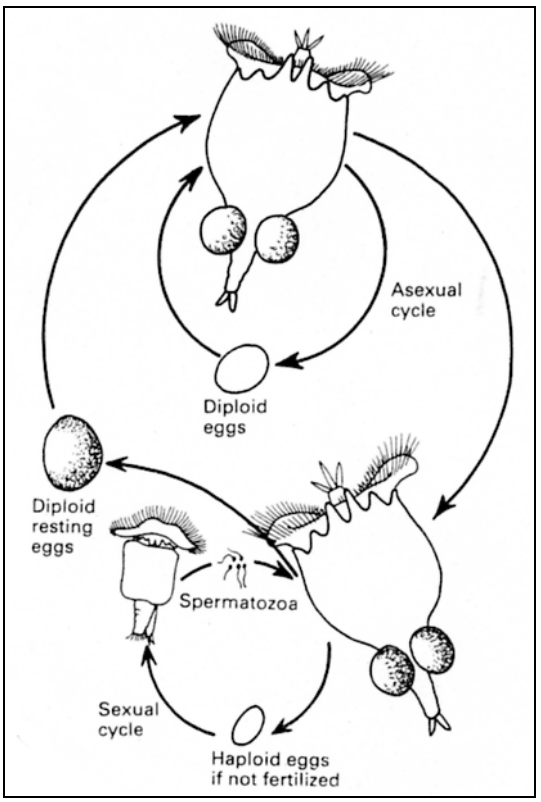

Figure 4.1. Life cycle of the rotifer displaying an asexual phase followed by a sexual phase (Barnes *et al*., 1993).

Several rotifer species have been identified in maritime Antarctica and the Antarctic Peninsula. Studies carried out at Signy Island found that lakes were dominated by *Philodina* sp. with lower numbers of *Ptygura crystallina*, *Collotheca ornata cornuta*, and *Notholca* sp. Apart from *Notholca* sp., the lower numbers of these species may be due to poor preservation (Dartnall and Hollowday, 1985; McInnes and Pugh, 1999; McInnes, 2003). *Notholca* sp. has also been identified within lake sediment

cores from Lake Boeckella (Gibson and Zale, 2006). Comparisons to these lakes can be made with Livingston Island as they have similar geographical locations.

4.1.2 Crustacean zooplankton

Microscopic crustaceans belong to the phylum Arthropoda, and are characterised by having segmented bodies that can be divided into three regions, the head, thorax and abdomen. In some taxa the first two regions are fused, where the head and thorax are combined and covered by a carapace. (Brönmark and Hansson, 2005). In freshwater, the truly planktonic Crustacea are dominated almost completely by the cladocerans and copepods (Wetzel, 2001).

4.1.2.1 Cladocerans

The sub-order cladocera are small, generally transparent organisms, and are generally referred to as water fleas. The body is disc shaped and covered with a carapace. The mouthpart consists of large chitinised mandibles that grind food particles. A pair of small maxillules are used to push food between the mandibles and a median labrum that covers the other mouthparts (Wetzel, 2001; Brönmark and Hansson, 2005). Most are pelagic filter feeders, mainly eating algae, and to some extent bacteria. The most well known genus is *Daphnia*, which is the major herbivore in many lakes (Brönmark and Hansson, 2005).

Cladocera are able to reproduce parthenogenetically. Females use the space between the carapace and body as a brood chamber, where eggs develop into embryos and eventually assume the shape of adults, which are then released into the water. Parthenogenetic reproduction continues until favourable conditions arise, and then some eggs develop into males and others into haploid eggs that require fertilisation (Fig. 4.2) (Cole, 1979; Brönmark and Hansson, 2005). Induction of male reproduction is enhanced by high population density or rapid reduction in food supply. Following fertilisation, the walls of the brood chamber of the female thicken, forming an ephippium, or resting egg. In favourable conditions, the ephippium hatches into new parthenogenetic females that rapidly start to reproduce (Brönmark and Hansson, 2005).

Cladocerans must moult their chitinous exoskeletons periodically throughout their lifetime to allow growth. The chitin is chemically inert, which preserves these remains making cladocerans among the best-represented groups in aquatic sediments, with most fragments identifiable to a species or at least group level (Hann, 1990). However, the exoskeletons are not preserved intact, as they typically disarticulate into head-shields, carapace, postabdomen, claws, antennules, mandibles, and ephippia (Hann, 1990). The cladoceran *Macrothrix* sp. has been identified in Limnopolar Lake and Chester Cone Lake, Byers Peninsula and has been associated in the bottom of these lakes with extensive carpets of moss (Rico *et al.*, 2003).

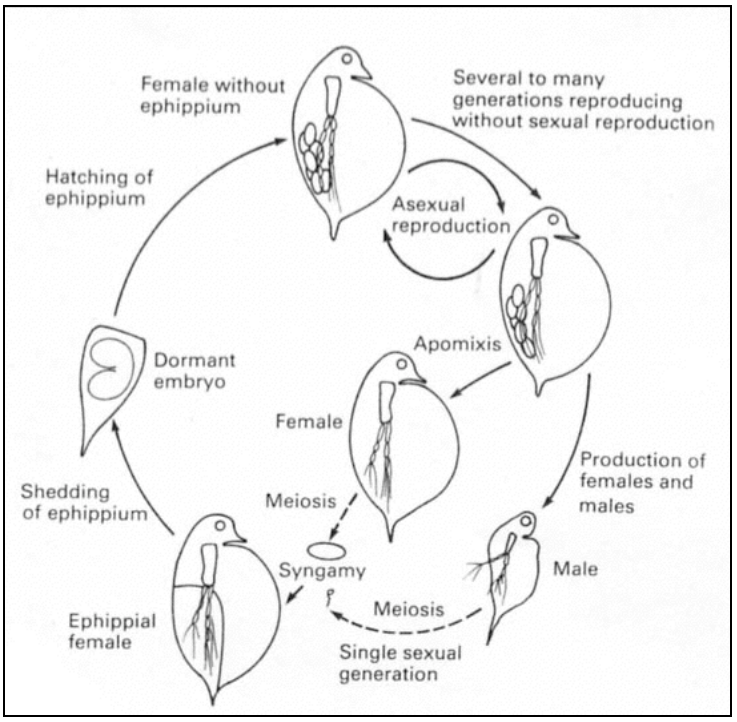

Figure 4.2. Life cycle of the cladoceran *Daphnia*, displaying parthenogenesis and sexual reproduction with the possibility of resting egg stages (Barnes *et al.*, 1993).

4.1.2.2 Copepods

Copepods have a cylindrical and segmented body, generally ranging in size from <0.5-2 mm, and are present in almost all freshwater. Their bodies comprise a head with well-developed mouthparts and antennae, a six-segmented thorax bearing swimming appendages, and a segmented abdomen (Barnes *et al.*, 1993). Copepods have a varied diet and may be herbivores, predators, detritivores, or omnivores. The feeding mode is raptorial as they lack filtering mechanisms (Hansson and Tranvik,

2003; Brönmark and Hansson, 2005). Copepods generally reproduce sexually, and when eggs are fertilised they are extruded in one or two egg sacs. After hatching, eleven or twelve larval stages follow before the adult copepod appears. In suboptimal conditions, copepods may produce resting eggs (Brönmark and Hansson, 2005).

Approximately 100 freshwater species of copepod are known to exist in planktonic and benthic environments. However, copepods do not preserve well in sedimentary records due to weakly scleritised body segments. Copepod species are typically represented in Quaternary sedimentary records by the preservation of faecal pellets and relatively durable male spermatophores (Cohen, 2003). The copepod species *Boeckella poppei* has been recorded from lake sediments from Lake Boeckella, northern Antarctic Peninsula (Gibson and Zale, 2006), and within Limnopolar Lake and Chester Cone Lake, Byers Peninsula (Rico *et al*., 2003; Bayly *et al*., 2003).

4.1.2.3 Branchipoda

The Branchipod *Branchinecta gainii* is the largest lacustrine organism found within freshwater Antarctic lakes, and can exceed a length of 15 mm (Ellis-Evans, 1996b; Peck, 2004). Embryos of *Branchinecta gainii* develop within eggs with two membranes. After breaking through the inner egg membrane they hatch and develop within a thin outer membrane. Two nauplii stages and a juvenile phase follow into adults with distinct featured and sexual dimorphisms with the potential to develop resting eggs (Jurasz *et al.*, 1983).

The distribution of these organisms is strongly influenced by their adaptation to survive in fluctuating water chemistry and extremely low temperatures. Adaptation for surviving cold temperatures within this species includes the utilisation of antifreeze mechanisms and the production of cysts that can survive temperatures of -20 °C (Peck, 2004).

Branchinecta gainii remains have been identified in lake sediment records from James Ross Island, Antarctic Peninsula; Signy Island and King George Island, maritime Antarctica; and Chester Cone Lake, Byers Peninsula. *Branchinecta gainii* is

also found within the current biota of Limnopolar Lake (Jurasz *et al.,* 1983; Björck *et al.,* 1996; Peck, 2005; Rico *et al.,* 2003).

Studies carried out by Björck *et al.* (1996) found that *Branchinecta gainii* occur in freshwater Antarctic lakes with varying nutrient levels where well-developed benthic communities occur or in organic rich sediments from autochthonous and allochthonous carbon inputs. *Branchinecta gainii* generally colonise lakes with relatively low mineral loadings of inorganic particles, such as tephra and other clastics, as they reduce cyanobacterial mat growth, limiting potential food sources for the species (Björck *et al.,* 1996). The disappearance of *Branchinecta gainii* on James Ross Island, identified by Björck *et al.* (1996), has been attributed to an increase of minerogenic matter caused by glacial erosion and meltwater inflow.

4.1.3 Chironomids

Midges belong to the order Diptera, with the family Chironomida being the most dominant of all aquatic insects. Dipterans vary greatly in morphology, but the main common characteristic is the absence of legs on the segments of the thorax (Usher and Edwards, 1984; Brönmark and Hansson, 2005). They typically feed on periphytic algae or detritus particles, and have the ability to filter out particles from water drawn in through the case (Cohen, 2003; Brönmark and Hansson, 2005). Predation and competition are unlikely to have significant impacts on Antarctic chironomid species, as there are no adequate predators (Convey and Block, 1996). They are a keystone species in freshwater ecosystems due to their high productivity (Hann and Reinhardt, 2006). Remains of dead larvae and carapace parts during larval moulting occur abundantly as fossils within lake sediment records, and are therefore important palaeoecological tools (Walker and Mathewes, 1987).

Only two species of chironomids occur naturally in maritime Antarctica: *Belgica antarctica* and *Parochlus steinenii*, both of which have been documented on Byers Peninsula (Cranston, 1985; Allegrucci *et al.,* 2005). A third chironomid species endemic to South Georgia, *Eretmoptera murphyi*, was accidentally introduced via human vectors to Signy Island in 1967 (Allegrucci *et al.,* 2005). *Belgica antarctica* is

endemic to maritime Antarctica, whilst *Parochlus steinenii* is found in the high Andes, Tierra del Fuego, South Georgia and the South Shetland Islands, Antarctica (Convey and Block, 1996; Allegrucci *et al.*, 2005; Convey and McInnes, 2005; Hann and Reinhardt, 2006). Adaptations of these organisms to cold environments has been attributed to a range of cryo-protectants, including glycerol; erythritol; trehalose; glucose; fructose; and mannitol, that have been identified in extracts of *Belgica antarctica* and *Eretmoptera murphyi* larvae (Usher and Edwards, 1984; Convey and Block, 1996).

Parochlus steinenii is a fully winged chironomids, whilst *Belgica antarctica* and *E*retmoptera *murphyi* have reduced wings, which is often a characteristic associated in Dipterans that exist in isolated environments and in areas where low temperatures and high winds restrict the possibility for flight (Convey and Block, 1996). As a fully flying species, and with populations occurring in the sub-Antarctic and South America, the species *Parochlus steinenii* has great potential to colonise other locations across the Antarctic (Convey and Block, 1996).

Studies carried out by Convey and Block (1996) identified that adult emergence of these chironomid species generally occurs during spring and early summer, with males emerging before females. Copulation immediately follows, and after successful fertilisation a single batch of eggs is laid within a gelatinous matrix. After hatching the larvae remain within this matrix before emerging onto the substrate. Four larval stages follow leading to a pupation period. Females that fail to copulate lay batches of unfertilised eggs, suggesting that parthenogenesis does not occur. (Convey and Block, 1996).

4.1.4 Tardigrades

Tardigrades, commonly called water bears, are generally considered to be a phylum, although their phylogenetic position has been strenuously debated. Recent molecular studies with 18S rRNA have shown that tardigrades are a sister group of the arthropods (Nelson and Marley, 2000). They differ from the arthropods in that they lack an exoskeleton and jointed legs (the basic arthropod features), and their bodies

are not segmented (Barnes *et al*., 1993). They do, however, posses four pairs of legs, ending in claws that are repeated along the length of the body, which they use to crawl using extrinsic muscles. They have soft bodies and a pseudocoelomic body cavity forming a hydrostatic skeleton that also functions in circulation and respiration (Barnes *et al*., 1993; Nelson and Marley, 2000). All species are suctorial feeders, having a muscular pumping pharynx with a pair of buccal stylets that can be protracted through the mouth to pierce the prey. Prey consumed may include algae, other plant cells, rotifers, nematodes and other tardigrades (Barnes *et al*., 1993).

All tardigrades are aquatic, as they require a film of water to remain active, however, they are capable of entering cryptobiosis when environmental conditions are unfavourable. Five types of latency have been identified in tardigrades: encystment, anoxybiosis, cryobiosis, osmobiosis, and anhydrobiosis. When a tardigrade is in a latent state, metabolism, growth, and reproduction are reduced or cease temporarily and resistance to environmental extremes such as cold, heat, drought, chemicals and ionising radiation is increased (Nelson and Marley, 2000). Studies carried out by Everitt (1981) found that tardigrade species survive in Antarctic regions by over-wintering in a cryobiotic state.

Tardigrade taxonomy is based primarily on the morphology of the claws, buccal-pharyngeal apparatus, cuticle and eggs. However, remains of adult tardigrades are rarely recorded in lake sediments as tardigrade bodies and exuvia decompose rapidly after sedimentation (Gibson and Zale, 2006). Therefore, the identification of sub-fossil tardigrade species is generally dependent on eggshell morphologies. Freshwater tardigrades produce either smooth shelled eggs, lain in the exuvium, or ornamented (processes, reticulations and pores) eggs laid freely. The shape of eggshell ornamentation varies widely among tardigrades and is generally species specific, which means that egg type (smooth or ornamented) becomes a valid taxonomic character at the generic level (Dastych, 1984; Bertolani *et al*., 1996; Nelson and Marley, 2000).

The presence of extensive cyanobacterial mats and epiphytes within maritime Antarctic lakes, as well as short food chains and a lack of predators, results in very large populations of benthic tardigrades within most freshwater lakes (McInnes and

Pugh, 1999; Nelson and Marley, 2000; McInnes, 2003). Several tardigrade species have been recorded on Signy Island, which has a climate similar to Livingston Island, including *Dactylobiotus* cf. *ambiguus*; *Diphascon* spp; *Acutuncus antarcticus*; *Isohypsibius asper*; *Isohypsibius laevis*; and *Isohypsibius papillifer* (McInnes and Pugh, 1999; McInnes, 2003).

4.1.5 Diatoms

Diatoms are unicellular algae that are common in most aqueous environments throughout the world, and are commonly reported in many Antarctic lakes and streams (Jones *et al*., 1993). Due to their siliceous frustules, diatoms are generally well preserved in lake sediments enabling identification of remains to typically species level. Additionally, several species are often recorded at abundant levels in lake sediment records making them ideal for studying past Antarctic environmental conditions (Björck *et al*., 1991a; Jones *et al.*, 1993; Martinez-Macchiavello *et al*., 1996; Roberts and McMinn, 1999). Compositions of diatom species is strongly related to lake water chemistry with responses to fluctuating pH, salinity, and nutrient levels in lake systems being identified with changes in the diatom community (Jones *et al.*, 1993).

Numerous diatom species have been recorded in lake sediments around maritime Antarctica and the northern Antarctic Peninsula. Studies carried out by Jones *et al.* (1993) identified three main groups on the basis of diatom assemblages from Byers Peninsula and Signy Island, and found that these groups were broadly similar to the groups identified by water chemistry alone. It was concluded from this study that diatom distributions in maritime Antarctica are strongly related to the chemical constituents in the lake environment.

It has been identified that lakes in Livingston Island have higher silicate and lower potassium and nitrate values, with the additional sources of silica being attributed to tephra inputs into the lake (Björck *et al*., 1991a; Jones *et al.*, 1993). Björck *et al.* (1991a) found that the domination of the diatom species *Stauroneis*, also recorded in present day Limnopolar Lake, at a depth of 63 cm was related to a tephra input that has increased the availability of silica content in the lake (Camacho *et al.*, 2003a).

Studies have also concluded that the diatom assemblages from maritime Antarctica and the northern Antarctic Peninsula are dominated by cosmopolitan species. Studies carried out by Björck *et al*. (1993) on Lake Åsa, Livingston Island, identified 92 diatom taxa, most of which were cosmopolitan. It has been assumed that the absence of Antarctic diatom species may be related to their lack of morphological or physiological characteristics that would enable them to survive prolonged periods of ice cover (Björck *et al.*, 1991a; Jones *et al.,* 1993).

4.2 Preservation of remains

Nearly all groups of animals leave at least some identifiable morphological remains in lake sediments. At the microscopic level, the most abundant animal remains in sediments are those of ostracods, cladocera, midges and, under favourable conditions, shells, egg cocoons, resting eggs of rotifers and copepod spermatophores. The preservation of organism remains in the sediment is typically incomplete, and the extent of preservation depends both on the type of organism and the environmental conditions that prevailed at the time of sedimentation (Wetzel, 2001). Cladocera and chironomid midges have the most abundant and diversified fossilised records within freshwater lakes (Wetzel, 2001).

Sedimentary columns and associated stratigraphic columns will provide a temporal and spatial record of Antarctic freshwater lake organisms throughout the lifetime of the lake system. Time scales can be applied through the use of sedimentary dating techniques such as fossil horizons, varve laminations, tephrochronology, and palaeomagnetism.

4.3 Effects of tephra on Antarctic lake ecosystems

Tephra impacts on Antarctic lake communities have in general been poorly studied, although in regions such as the northern Antarctic Peninsula, tephra impacts have largely shaped palaeolake ecosystems. Studies carried out by Tatur *et al.* (1999) found that the impact of tephra fallout was considered to be an important factor in the

modification of the biota within Hotel Lake, King George Island. It was documented that the repeated deposition of tephra from Deception Island resulted in a pyroclastic shock for the diatom ecosystem of the lake, with some taxa becoming extinct within the lake, some species gradually disappearing, and some adapting to the new environmental conditions (Tatur *et al*., 1999; Tatur *et al*., 2004).

Investigations carried out by Björck *et al*. (1993) found a 5000 year-long section of sediment core that was influenced by frequent tephra fallout on Byers Peninsula, playing a major role in the lake's ecosystem from 4700-4600 and 2800-2500 years BP. They concluded that the tephra fallouts from Deception Island had a significant role within the lake due to: the proximity to Deception Island; frequent Deception Island eruptions; small catchment area; the fact that the lake is only fed via glacial/snow meltwater and precipitation; and the low chemical stability of tephra (Björck *et al*., 1993). Björck *et al*. (1991a) found sediment layers with high tephra input had low LOI values located at 2700, 1150, and 750 years BP. Correlations between high tephra concentrations and high nitrogen levels were also identified. These changes have been attributed to moss surfaces having a higher heat absorbency due to a darker surface which could have created a rise in surface temperature, prompting greater decay rates of tephra minerals and a subsequent increase in the supply of mineral nutrients (Björck *et al*., 1991c). It was identified that systems completely destroyed by tephra inputs would start to be recolonised by heterotrophic microbes within one year of the volcanic event (Smith, 1985).

Chapter Five

METHODS

5.1 Sediment Core

During the Antarctic Season of 2002/2003, several sediment cores were obtained from Limnopolar Lake on Byers Peninsula, Livingston Island by the Spanish research group Limnopolar, led by Antonio Quesada. The sediment cores were extracted using a modified hybrid Glew corer and Kajak corer from the ice above the lake. The sediment core examined in this study was 29.2 cm in length and did not reach bedrock.

The gravity core was sectioned on site into 0.2 cm sections (0-10 cm), 0.5 cm sections (10-25 cm), and 1.0 cm sections (25-29 cm). The sections were then transferred into labelled whirlpak bags and transported to Spain. During September 2004, the core was transported from Spain to Hobart and stored at a constant temperature of 4°C. The author was not involved in the acquisition or sectioning of the core but was responsible for the storage and treatment of the sediment core once it arrived in Hobart. Studies of other aspects of the core, such as diatom assemblages, are being undertaken at the Universidad Autonoma de Madrid.

5.2 Physical analysis

5.2.1 Percentage organic carbon

Loss on ignition at 550 °C (LOI_{550}) was used to estimate the percentage of organic material within the sediment. The samples are heated in scintillation vials in an oven at 105 °C and weighed to produce a dry mass; the dried sediment was then

transferred to crucibles and re-weighed. The samples were heated in a muffle furnace to a temperature of 550 °C overnight and re-weighed. LOI_{550} represents only an estimate, not an accurate value, of the percentage of organic material and was determined by the loss in mass after heating at 550 °C, and expressed as a percentage of dry mass, as seen in equation 5.1.

$$\%LOI_{550} = \frac{(M_D - M_{550})}{M_D} X100 \quad (5.1)$$

5.2.2 Inorganic carbon

Loss on ignition at 950 °C ($*LOI_{950}$) was used to estimate the percentage of calcium carbonate within the sediment. This procedure utilised the same samples used for the LOI_{550}. After the samples had been heated in a muffle furnace at 550 °C and weighed they were returned to the muffle furnace at a temperature of 950 °C overnight and re-weighted. $*LOI_{950}$ represents only an estimate, not an accurate value, of the percentage of calcium carbonate, and was determined by the loss in mass after heating at 950 °C, with the loss being attributed to CO_2 combustion. $*LOI_{950}$ was then converted to account for CO_2 liberation by multiplying $*LOI_{950}$ by the molecular weight of calcium carbonate divided by the molecular weight of CO_2, providing an estimate of carbonate content, expressed as a percentage of dry mass, as seen in equation 3.6.

5.2.3 Chemical treatment for tephra selection

The sediment samples were chemically treated to eliminate unwanted components, such as organics and certain minerals, to aid in the isolation of tephra shards. The procedure set out below is a slightly altered version of that found in Rose *et al.* (1996).

Approximately 1-2 g of wet sediment was transferred into a polyethylene tube and heated in an oven at 50 °C overnight to evaporate any water in the sample. 0.1-0.2 g of dried sediment was accurately weighed and transferred to nalgene test tubes. 2 mL of 30% H_2O_2 was added to each sample and left overnight at room temperature. An additional 5 mL of H_2O_2 was then added to each sample, which was then heated in a water bath at 80-90 °C for 3 hours. Once cooled, 30 mL of distilled water was added to each sample and centrifuged for 5 minutes at 1500 rpm. A 5 mL syringe was used to remove as much supernatant as possible. 5 mL of 0.3 M NaOH was added to each sample and mixed well with a lid on the nalgene test tubes. The samples were heated in a water bath for 3 hours. Once cooled 30 mL of distilled water was added to each sample and centrifuged for 5 minutes at 1500 rpm. The supernatant was extracted using a 5 mL syringe. 5 mL of 3 M HCl was added to each sample and was heated in a water bath at 80-90 °C for 1 hour. Once cooled, 30 mL of distilled water was added to each sample and centrifuged for 5 minutes at 1500 rpm. As much supernatant as possible was removed using a 5 mL syringe. This washing and centrifuging procedure was repeated before transferring the residue of each sample into pre-weighed scintillation vials.

5.2.4 Counting of Tephra

The sediment remaining after the above treatment was used to prepare microscope slides to aid in the identification and evaluation of single tephra shards.

A small amount of the sediment was further sub-divided into separate pre-weighed scintillation vials, allowing for the calculation of before and after weights. This was achieved by 3/4 filling the original scintillation vial containing the treated tephra and strongly mixing to provide a homogeneous mix of the sediment suspended in the solution. A Pluripet pipette set to 200 microlitre (µl) was then inserted into the scintillation vial to extract some sediment. This process had to be performed very quickly and efficiently to obtain a homogeneous sample, as the tephra settled out quickly from the solution. The extracted sediment was then placed into a clean pre-weighed scintillation vial and the extraction procedure repeated so that only a small

homogeneous amount of the sediment was used to prepare an evenly and thinly covered microscope slide. The selected 200 µl of sediment was then carefully placed onto a cover slip and heated on a hot plate set on low for at least 2 hours to dry the sample on the cover slip. A drop of Naphrax, a diatom mountant, was then placed on top of the sample. The microscope slide was then quickly placed on top of the cover slip before the Naphrax began to harden. The slides were then placed on a hot plate on a low setting for a further hour to let the Naphrax set.

To recognize tephra shards, the slides were first examined under cross-polarised light. The shards were distinguished on the basis of morphology, vesicularity and isotropy. The tephra slides were then examined under a binocular microscope with attached digital camera under a X100 magnification. Photographss of tephra shards were taken to aid in the counting process of the shards. Each tephra shard was counted and recorded to calculate the number of shards at a particular depth in the sediment core, expressed as the concentration of shards per gram of dried sediment (g_{dm}^{-1}), as shown in equation 5.2.

$$Concentration = \frac{100n}{pm} \tag{5.2}$$

Where n = number of shards on slide

p = percentage of final residue evaporated onto cover slip

m = mass of dried sediment utilised

However, it must be stated that the techniques used to prepare the tephra slides for counting purposes introduced errors. The problem lies in the amount and distribution of the tephra during the slide making process. This method did not enable an even spread of tephra shards across the cover slip, resulting in slides that are, in some cases, several grain levels thick. Accurate counting was then impossible as each single shard could not be identified and counted. Therefore, the tephra count should be treated with caution, as it is an estimate only, though it would imply a systematic error. A possible solution to this problem would be the settling of tephra through a

known amount of water onto a cover slip in a known area. This technique may limit the amount of layering on the slide so that a single grain-thick layer can be produced.

5.2.5 Size distribution of tephra

Photographs taken of tephra slides, prepared as described in Section 5.2.4, were examined with an image analysis program, NIH Image. In this program, tephra shards were identified and measurements taken of shard length (along the longest axis) and shard area.

5.2.6 Chemical Analysis of Tephra

5.2.6.1 Preparation of Sediment for electron probe micro analysis (EPMA)

Approximately 1 g of sediment was dried in polyethylene tubes at 50 °C. Washing of the sediment was required to aid in the identification and extraction of single tephra shards for the EPMA procedure. Washing was accomplished by transferring the dried sediment into 50 mL beakers. Forty mL of distilled water was added to the sediment and mixed thoroughly to break up the dried sediment. The beaker was placed into a sonicating bath for 2 minutes. The excess water was carefully removed. This washing procedure was repeated until the supernatant water was clear. The remaining sediment was then dried in an oven at 50 °C.

The dried sediment was examined under a dissecting microscope and shards of tephra were identified on the basis of morphology, vesicularity and colour. Once a tephra shard was identified, it was carefully extracted using a hypodermic syringe and placed on double sided tape with the shape of the mould traced onto it. Tephra shards were aligned in lines along the double-sided tape to aid in identification during the EPMA process; a map of the tephra mould was also kept.

A small plastic container was selected to prepare the solution for the mould, the container was placed on the scales and the weight tared. 5 gm of araldite (polymer)

was poured into the container followed by 0.85 gm of hardener HY956 (catalyst), making a total weight of 5.85 gm. The mixture was carefully stirred with a plastic rod, to dissipate any bubbles, and was placed in an oven at 50 °C for 2 minutes to gently warm. The double-sided tape was also heated. A little bit of the mould mixture was poured into the mould to prevent any leakage, and was placed back in the oven at 50 °C for 5-10 minutes to harden. The rest of the mixture was then poured into the mould and placed in the oven for 1-2 hours at 50 °C to harden.

After the mould had set it was carefully removed from the double-sided tape. The mould was then sanded with 5 µm alumina, wet and dry paper 1200, and finally with 0.3 µm alumina to bring the tephra shards to the surface of the mould. The mould was then buffed and polished to bring up a clean and smooth surface. It was imperative at this stage to keep the mould free of grease and dust.

5.2.6.2 Electron probe microanalysis (EPMA)

The EPMA process was carried out using a Cameca SX50 analyser, with a beam size of 20 µm, located at the Central Science Laboratory, University of Tasmania. All results are calculated on an anhydrous basis by adjusting totals to 100%.

5.3 Dating

5.3.1 Dating of sediment

2 g of two samples (depths of 0.2 cm and 28.0 cm) were carefully extracted and placed into whirlpak bags under sterile conditions to prevent any contamination of the samples. These were sent to the Australian Nuclear Science and Technical Organisation for Accelerated Mass Spectrometry (AMS) radiocarbon dating of the organics within the sediment sample. The results were then entered into CALIB, a radiocarbon calibration program that converts the carbon years into calendar years (Stuiver *et al*., 2005).

5.3.2 Dating of tephra

The geochemical signatures from each tephra event were compared against historical records of volcanic eruptions within the Antarctic and sub-Antarctic, as well as events recorded in the southern hemisphere and globally, when wind conditions and the volume of volcanics erupted from a particular volcanic event had the potential for the transportation and deposition of tephra from the volcanic source to Limnopolar Lake, Byers Peninsula. Once possible volcanic events for the volcanic material found within the lake were identified, the geochemical signatures of the tephra in the lake were compared against the geochemical signatures of the tephra from the source volcanic eruption to confirm the event. When a volcanic event has been successfully related to a tephra horizon within the lake it was possible to determine the date of the tephra through the use of historical recording of the event and dating of the volcanic rocks that were erupted during that volcanic eruption. Unless a complete match can be made between a particular tephra horizon in the lake and a recorded volcanic eruption, the dating can only be an estimated age.

5.4 Biological Analysis

5.4.1 Preparation of Sediment

Approximately 1 g of wet sediment was placed in a specimen jar and distilled water added to disperse the sediment. To aid in the identification of remains the sediment was split into three size fractions: 200 µm, 100 µm, and 44 µm using sieves with mesh sizes of the desired class. After the sieving process each sediment size was then carefully backwashed into clean specimen jars and approximately 2 drops of 1 % Rose Bengal solution added and then left at 4 °C for at least 12 hours to enable thorough staining of biological remains.

5.4.2 Isolation of Remains

After the staining process the sediment was examined under a dissecting microscope through the use of sub-sampling into a Petri dish. When a possible remain was located notes were made on its physical features and photos were taken using a microscope mounted digital camera under the dissecting microscope. Higher-powered Zeiss and Olympus microscopes were used for later reference and identification purposes.

5.4.3 Identification of remains

Remains were identified to the highest taxonomic level with the aid of various publications and through personal communication with experts who are familiar with the identification of the types of organisms found within this study. Some of these experts include Dr John Gibson (IASOS, University of Tasmania), Dr Kerrie Swadling (School of Zoology, University of Tasmania), Louise Cromer (School of Zoology, University of Tasmania), Kristina Paterson (IASOS, University of Tasmania), Professor Andrew McMinn (ACE-CRC, University of Tasmania), and Dr Peter Convey (British Antarctic Survey).

5.4.4 Stratigraphical analysis

Occurrences of individual remains were counted throughout the depth of the core. This data was then fed into a program known as C2 to produce a stratigraphical representation of these results. A temporally constrained cluster analysis (CONISS) was obtained using the program Zone, which correlates the mathematical relationship between the various organisms within the lake using an incremental sum of squares (Grimm, 1987).

Chapter Six

PHYSICAL RESULTS

6 Introduction

This chapter will begin with the results of tephra analysis, including shard morphology, size distribution and EPMA results. The composition of the tephra shards in terms of silica content will also be presented and discussed. The chapter will then focus on the presentation of physical results from the sediment core, including organic and carbonate content of the sediment and radiocarbon dating results.

6.1 Shard morphology and size distribution

All shards from Limnopolar Lake (see Fig. 2.6 for location) were isotropic under cross-polarised light. Most tephra shards were pale brown and the predominant shards were angular and poorly to moderately vesicular (Fig. 6.1a-d). At a depth of 18.0 cm, there was an abrupt change in morphology to vesicular blocky shards and then a return to the predominant shard morphology from 19.0 cm. Few microcrystals, predominantly plagioclase, were present within tephra shards from Limnopolar Lake. There were rare occurrences of partially fluidal shards (Fig. 6.1e and 6.1f) that have smooth surfaces produced by melt surface tension.

The average length of the shards was between 100-150 μm. Few shards were greater than 200 μm (Fig. 6.2). There was an abrupt increase in shard size at 18.0 cm, to an average shard length of 290 μm. This change occurred at the same position as the distinct change in tephra morphology. Shard area distributions tend to reflect shard length.

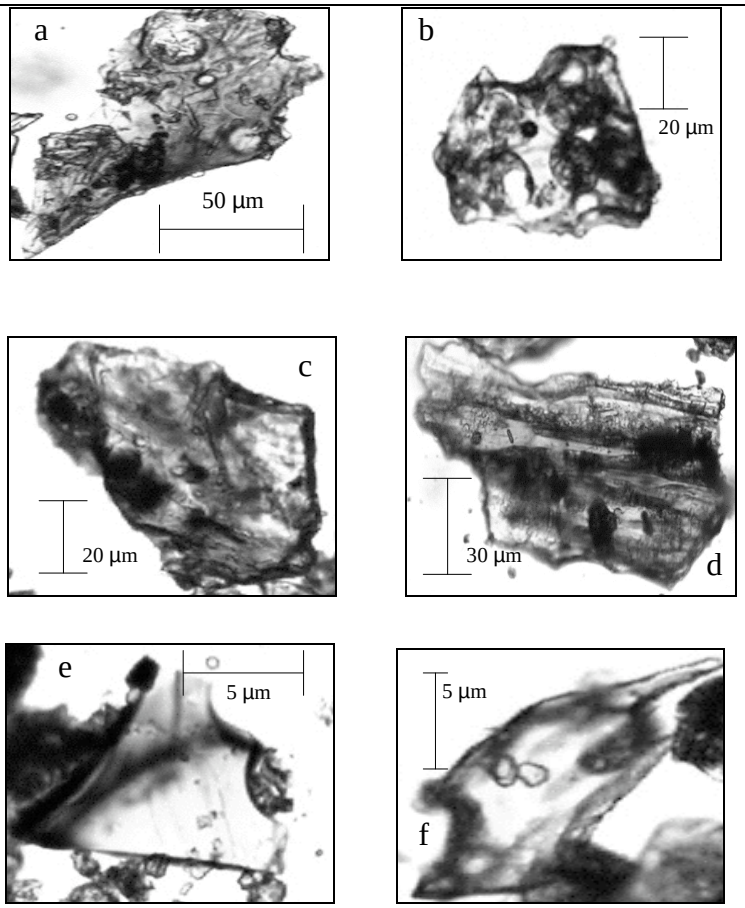

Figure 6.1. a) Moderately vesicular pumice shard from a depth of 15.0 cm in the sediment core; b) Moderately vesicular pumice shard from 22.0 cm; c) Poorly vesicular shard from 14.0 cm; d) Poorly vesicular shard from 7.0 cm; e) Partially fluidal tephra shard from 20.0 cm; f) Partially fluidal tephra shard from 24.0 cm.

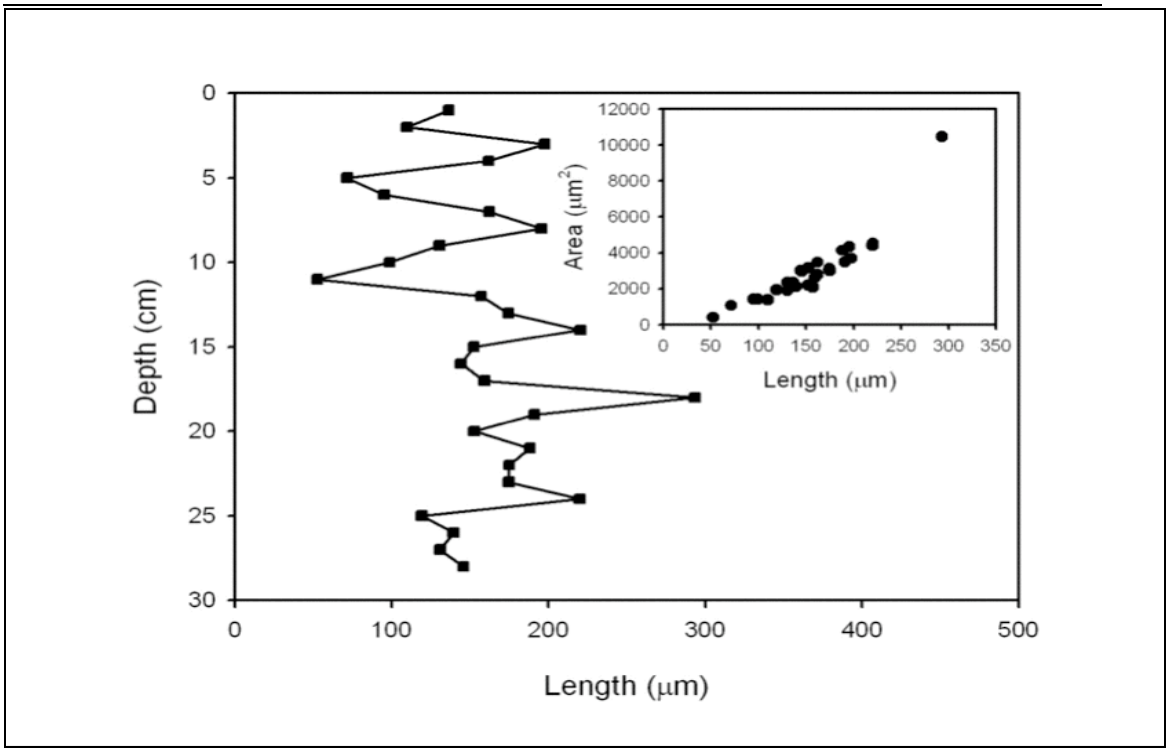

Figure 6.2. Average length of tephra shards in Limnopolar Lake. Inset graph displays the relationship between average shard length and average shard area.

6.2 Tephra abundance

The abundance of tephra shards was highly variable along the sediment core (Fig. 6.3). The tephra counts ranged from 16,400 g_{dm}^{-1} at 11.0 cm to a peak of 80,400 g_{dm}^{-1} at 17 cm. A background level of ~30,000 g_{dm}^{-1} was identified, representing the continual washing in of tephra from the surrounding catchment area. Five tephra horizons have been assigned to counts over the background level of 30,000 g_{dm}^{-1}. These are Horizon 1 at 22 cm with a count of 35,200 g_{dm}^{-1}; Horizon 2 at 17 cm, 80,400 g_{dm}^{-1}; Horizon 3 between 13-14 cm, 42,800-45,800 g_{dm}^{-1}; Horizon 4 at 6 cm, 53,000 g_{dm}^{-1}; and Horizon 5 at 3 cm, 79,200 g_{dm}^{-1}.

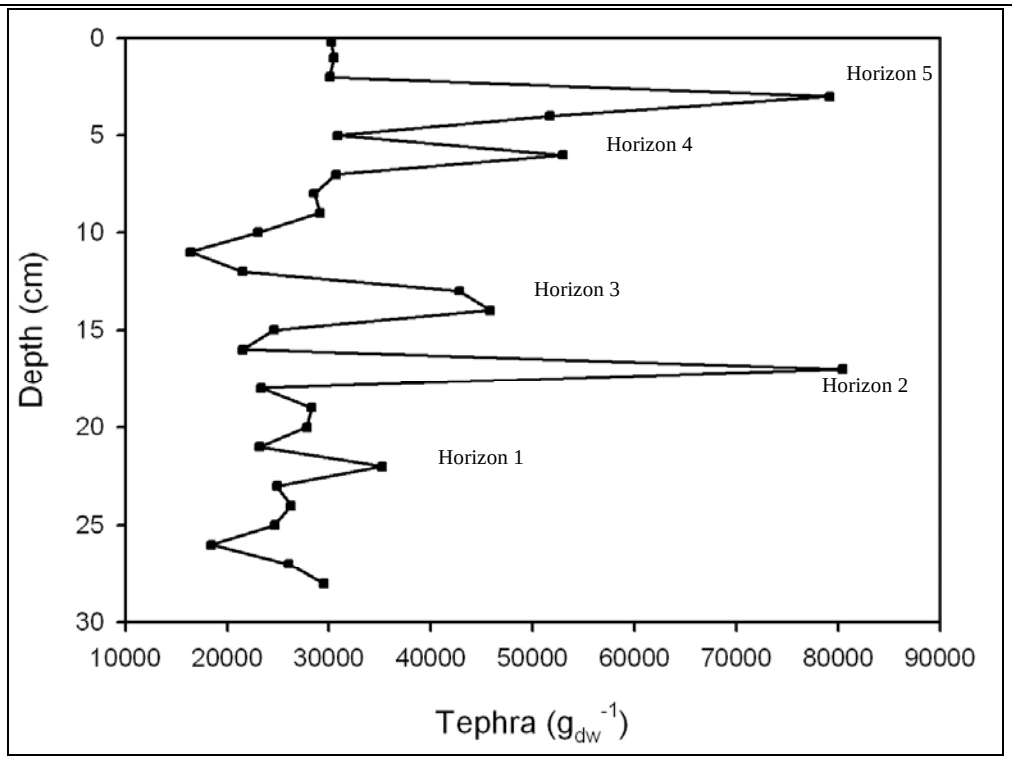

Figure 6.3. Tephra count of sediment core. Tephra abundances greater than 30,000 have been labelled as a tephra horizon.

6.3 Shard compositions electron probe micro analysis

Several shards (2-15) from each depth of core were analysed using an electron probe micro analyser. Each shard analysed had a total recovery rate of over 93%, with the loss being attributed to the instability of alkali metals (sodium and potassium) during the EPMA procedure. Complete analytical results for each shard analysed can be found in Appendix 1.

Each tephra shard was differentiated on the basis of silica content using the typical values for magma compositions (Table 3.1). The predominant composition of the tephra shards analysed was basaltic andesite. The remaining shards were composed of basalt, trachy-basalt and basaltic trachy-andesite. However, there was some variability within the other main oxides (iron oxide, magnesium oxide, sodium oxide, and potassium oxide) that were used to identify magma compositions.

Plots of MgO, FeO, and the sum of total alkalis (TAS diagram), provide the most valuable information in terms of tephra composition from Limnopolar Lake (Figs.

6.4-6.6). This presentation of chemical results of glass shards is the most common and accepted form found within the Antarctic Peninsula literature. These plots therefore aid in the process of correlating Limnopolar Lake tephra within the current tephrostratigraphy of the region and when comparing bulk rock compositions of various volcanic centres over the Antarctic.

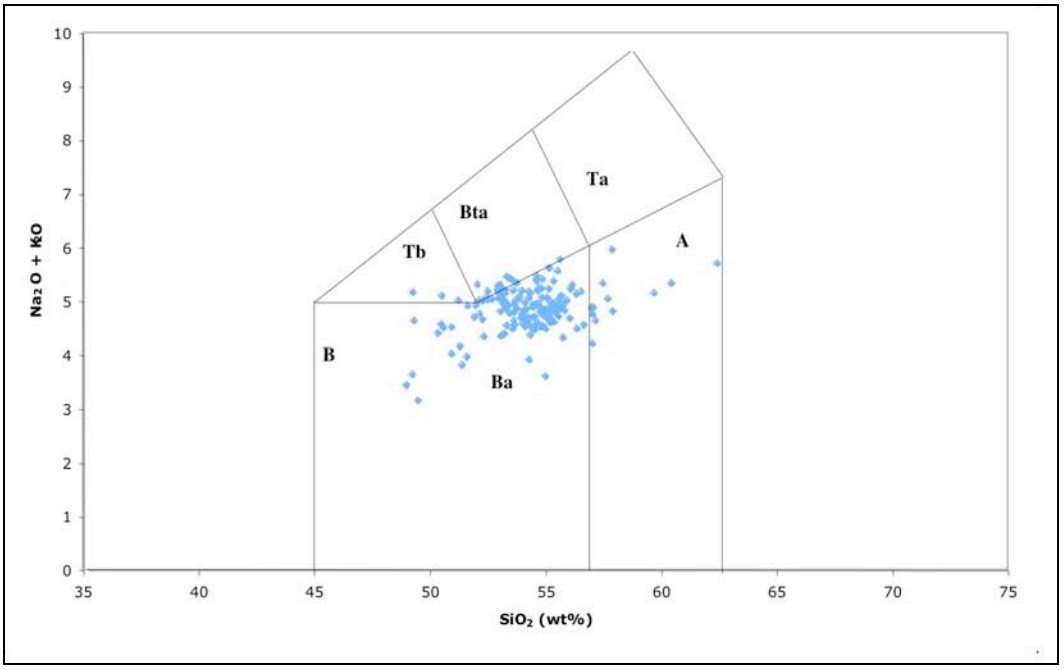

Figure 6.4. TAS diagram of tephra shards from Limnopolar Lake as devised from the IUGS classification scheme for volcanic rock (Le Maitre, 1989). B = basalt; Ba = basaltic andesite; A = andesite; Tb = trachy-basalt; Bta = basaltic trachy-andesite; Ta = trachy-andesite.

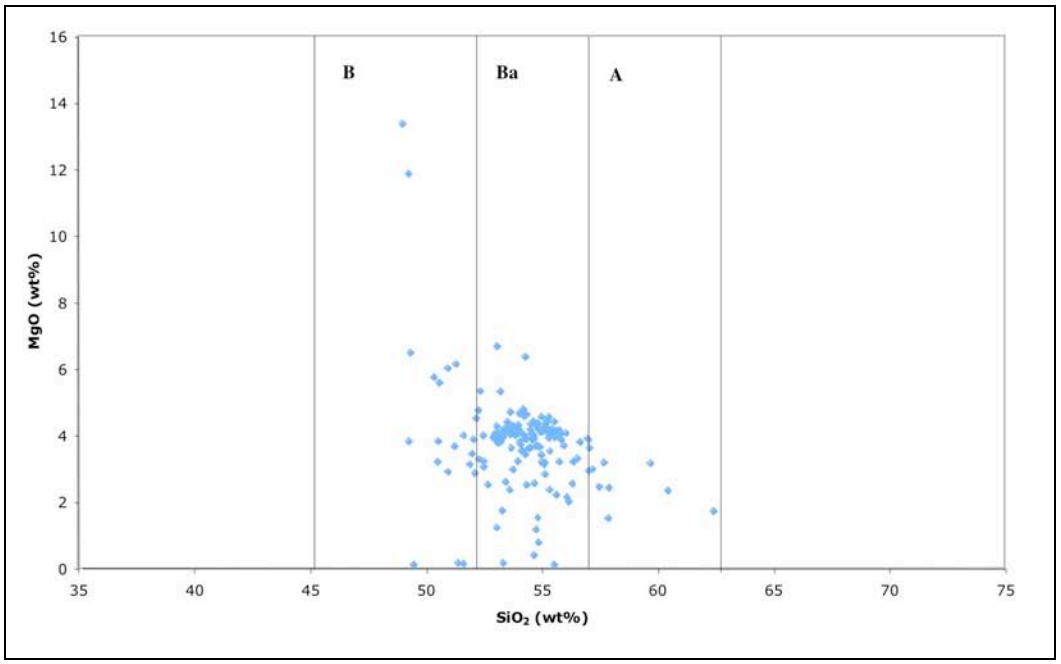

Figure 6.5. MgO vs. SiO_2 of tephra shards from Limnopolar Lake. B = basalt; Ba = basaltic andesite; A = andesite.

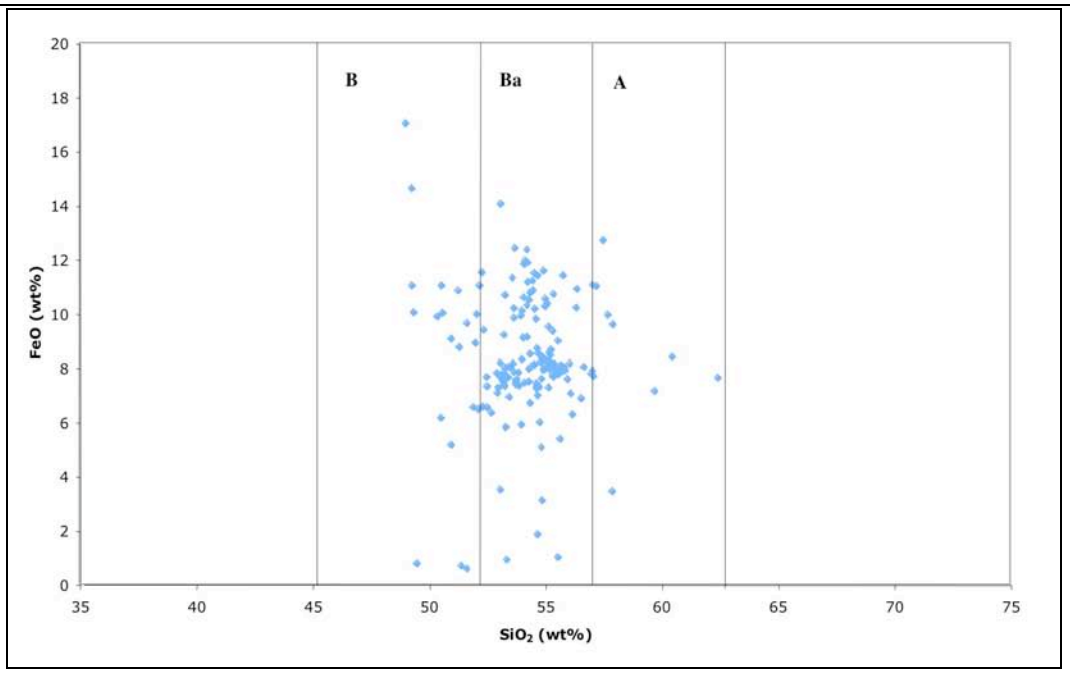

Figure 6.6. FeO vs. SiO_2 of tephra shards from Limnopolar Lake. B = basalt; Ba = basaltic andesite; A = andesite.

The Na_2O and K_2O levels of the tephra shards were fairly homogeneous; slightly lower values occur in association with basaltic tephra. The MgO content of the tephra shards were predominantly between 2-7 wt%, with slightly higher MgO levels associated with basaltic shards. There was a large total FeO range of the tephra, although most analyses were between 5-14 wt%.

The major element oxide abundances of the andesite and basaltic andesite tephra shards were well within the range of andesite and basaltic andesite shards identified by Hodgson *et al.*, (1998) (Table 6.1). The andesite layer was from Midge Lake, Livingston Island, and the basaltic andesite layer is from Sombre Lake, South Orkney Islands. Comparing the andesite and basaltic andesite composition ranges with other known tephra horizons from the local region confirmed that the composition of tephra from Limnopolar Lake fell within the range shown by other horizons that have previously been identified within the local area.

Table 6.1. Average compositions and ± standard deviation of tephra shards from Limnopolar Lake, Livingston Island (n = number of shards), compared to average composition of tephra shards from Midge Lake, Livingston Island and Sombre Lake, South Orkney Islands.

Element (oxide)	Basaltic andesite (Limnopolar Lake) n = 143	Basaltic andesite (Midge Lake) (Hodgson *et al.*, 1998).	Basalt (Limnopolar Lake) n = 13	Basalt (Sombre Lake) (Hodgson *et al.*, 1998).
SiO_2	55.27% ±0.9	53.84%	51.70% ±1.1	50.42%
TiO_2	1.82% ±0.5	1.88%	1.71% ±0.9	2.70%
Al_2O_3	16.62% ±2.4	16.48%	17.42% ±7.2	15.85%
FeO	8.46% ±2.0	8.16%	8.50% ±4.2	12.33%
MnO	0.17% ±0.0	0.20%	0.17% ±0.1	0.21%
MgO	3.79% ±0.1	3.43%	5.54% ±4.1	3.49%
CaO	8.25% ±0.9	7.97%	10.52% ±2.9	7.53%
Na_2O	4.35% ±0.4	5.05%	3.76% ±1.1	3.70%
K_2O	0.63% ±0.2	0.65%	0.40% ±0.2	0.35%

6.4 Organic carbon and carbonate content of sediment the core

LOI_{550} provides an empirical value for the percentage of organics within sediment. There was an overall general decline in LOI_{550} from the sediment core from Limnopolar Lake (Fig. 6.7). The LOI_{550} values generally increased with depth with a minimum of 2.8% at 4.6 cm and a maximum of 9.9% at 26 cm.

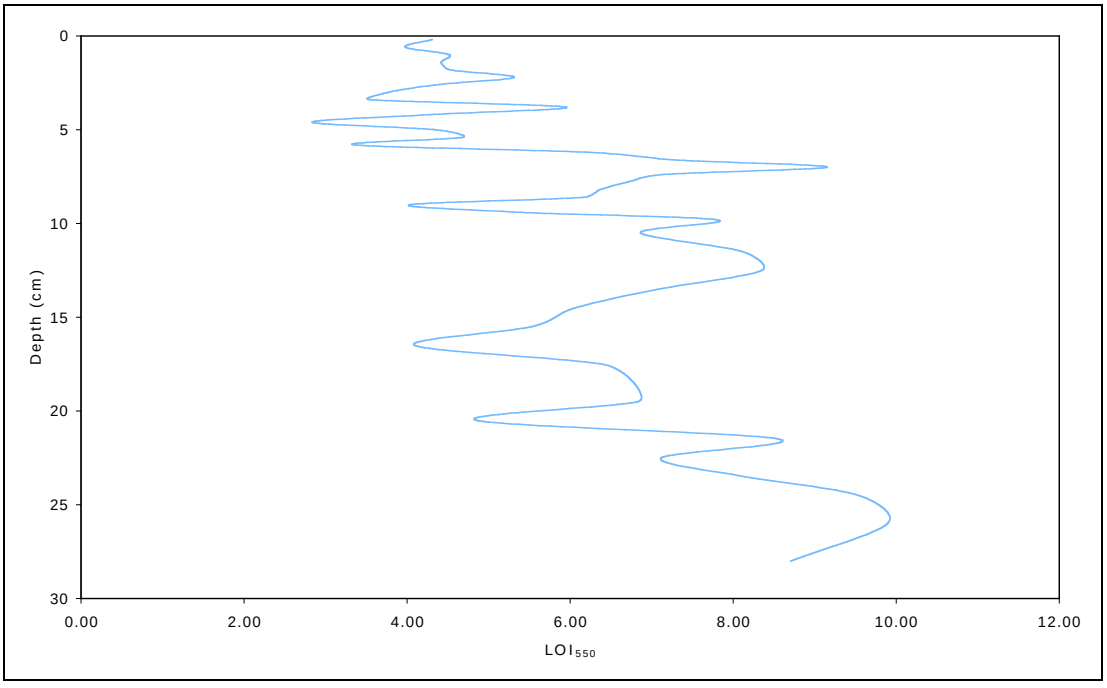

Figure 6.7. Estimate of the percentage organic carbon in the sediment core from Limnopolar Lake as determined by LOI_{550}.

*LOI_{950} provides an empirical value for the percentage of carbonates within the sediment core. *LOI_{950} values varied down the depth of the core (Fig. 6.8). There was a general decline of *LOI_{950} from 15-30 cm down the core with a maximum of 4.74% at 19.5 cm and a minimum of 0.92% at 16.5 cm. From 0-15 cm down the core there was a substantial increase in *LOI_{950} with a maximum value of 7.80% at 2.6 cm and a minimum of 1.09% at 4.6 cm.

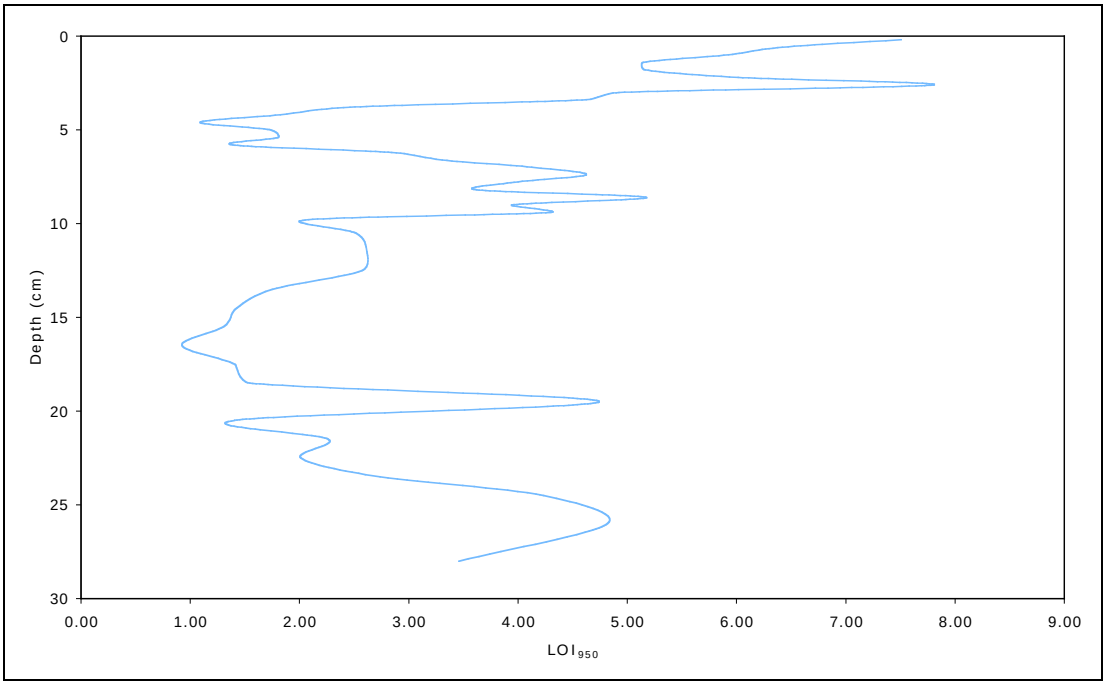

Figure 6.8. Estimate of the percentage $CaCO_3$ in the sediment core from Limnopolar Lake as determined by *LOI_{950}.

6.5 Radiocarbon dating

Organic material from two sediment samples (0.2 cm and 28 cm) was radiocarbon dated (AMS). The sample at 0.2 cm was found to be modern (< 50 ^{14}C years BP), whilst the sample at 28 cm returned at date of 2110 ± 50 ^{14}C years BP. This date was calibrated into calendar years using CALIB Southern Hemisphere calibration (SHCa104) 0 – 10000 cal BP (Table 6.2).

Table 6.2. Uncalibrated and calibrated radiocarbon dating at 28 cm.

Depth	*Sample reference*	*^{14}C age yr BP*	*95.4% (2σ) cal age min*	*95.4% (2σ) cal age max*	*95.4% (2σ) cal median*	*Calibration data*
28 cm	OZH859	2110 ± 50	cal BP 1891	cal BP 2148	BP 2020 ± 130	McCormac *et al.*, 2004

Precise sedimentation rates are difficult to determine as sedimentation rates fluctuate throughout time. Due to the fact that a single radiocarbon date was obtained for this study, a constant linear sedimentation rate was assumed so that approximate radiocarbon dates can be assigned to samples through the length of the core. The assumed sedimentation rate used in this study was 14 mm per 100 carbon years (Fig. 6.9).

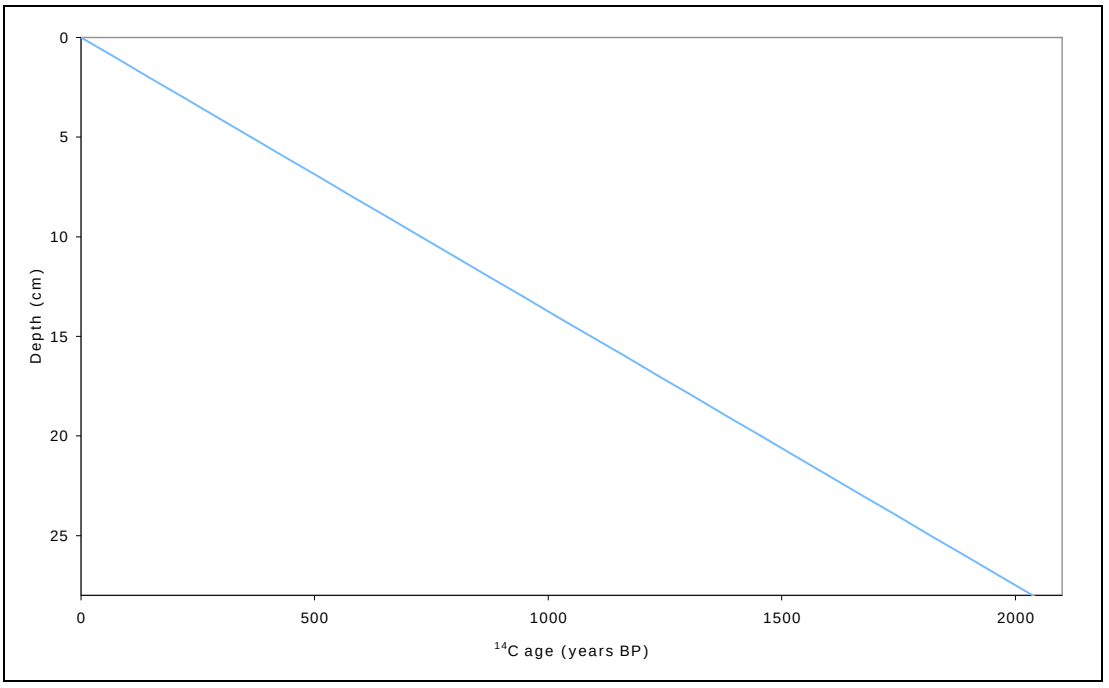

Figure 6.9. Linear sedimentation rate and radiocarbon dating for Limnopolar Lake.

Chapter Seven

ECOLOGY RESULTS

7 Introduction

Ten palynomorphs were clearly identified within the sediment core of Limnopolar Lake, including eggs, carapaces, and algal remains. The application of the term palynomorphs within this study has been used in the context of grouping remains with similar morphologies. Four of these palynomorphs have been identified to a species level. These remains are described within this chapter and their distributions in the sediment are displayed in a stratigraphical plot.

7.1 Biological Remains

The relative abundance of all of the remains within the sediment core is low until a dramatic increase in abundance levels at approximately 700 years BP. The abundance of organisms after this point remains relatively high through to present day sediments, with additional major peaks occurring within the surface sediments, and from 100-200 years BP. There are also three minor peaks of abundance levels from 250-500 years BP (Fig. 7.1).

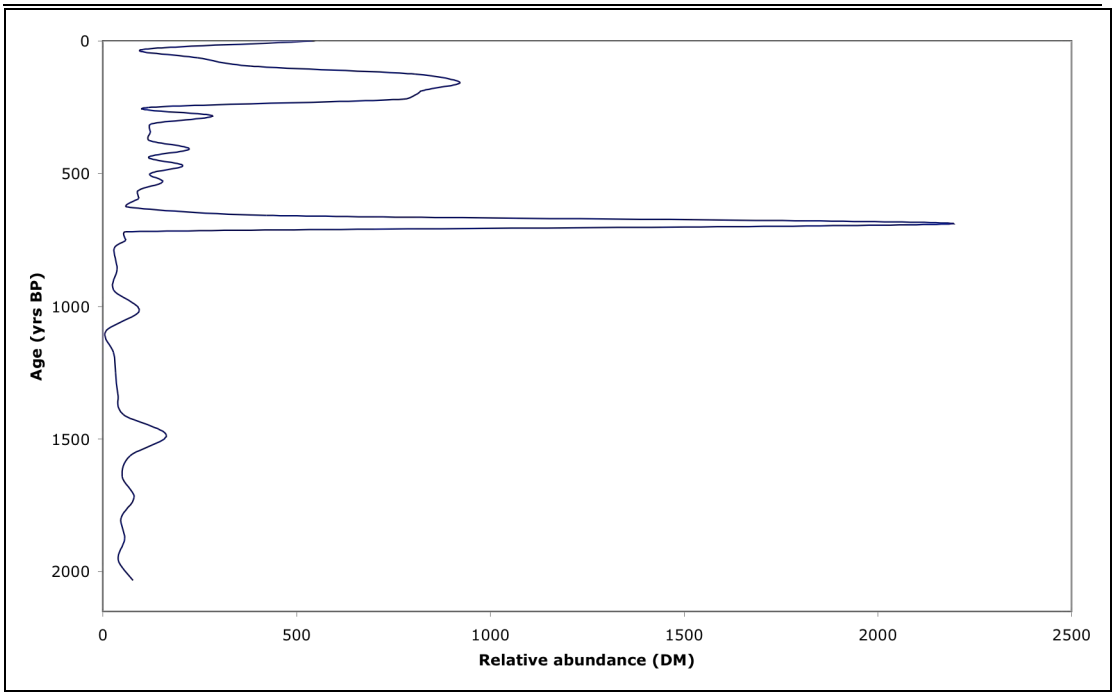

Figure 7.1. Relative abundance of all significant biological remains within the sediment core of Limnopolar Lake.

7.1.1 Palynomorphs

Branchinecta gainii – This palynomorph type stained extremely well with the rose Bengal, appearing bright pink. This palynomorph was large in size, up to 500 µm, and was spherical. All examples of this remain appeared to have a single concave opening extending halfway around the circumference of the membrane and several layers of the membrane can be identified. The morphology of this remain type suggests they are eggs of the species *Branchinecta gainii* (Fig. 7.2a).

Dactylobiotus cf. *ambiguus* – This palynomorph ranged substantially in size, from 50-200 µm, though they were predominately 100 µm in size. The remains stained relatively well with the rose Bengal appearing as a pale pink. The surface of the membrane contains un-bifurcated smooth processes that are cylindrical in shape. The morphologies of this remain indicate that it is from the tardigrade species *Dactylobiotus* cf. *ambiguus* (Fig. 7.2b. Note that this SEM image is not of a sample from Limnopolar Lake, but rather from Lake Boeckella (Gibson and Zale, 2006)). Only a single, unidentified adult tardigrade was observed at the top of the sediment core, 0.0-0.2 cm, this is most likely due to the poor preservation of these organisms.

The four pairs of appendages ending in claws are clearly visible, as are some of the internal organs and structures, such as the pharynx (Fig. 7.2c).

Parochlus steinenii – These palynomorphs were large in size, 200 µm, with some portions staining well with the rose Bengal whilst other sections remaining brown to dark brown. The morphology of these remains suggests that they are of the chironomid species *Parochlus steinenii* (Fig. 7.3). Many parts of the pupa and adult are clearly distinguishable (Fig. 7.4a thorax of adult; Fig. 7.4b adult male; Fig. 7.4c head capsule and compound eyes; Fig. 7.4d wings and legs of pupa; Fig. 7.4e pupa segments with laterally protruding spinelike processes; Fig. 7.4f tail of pupa).

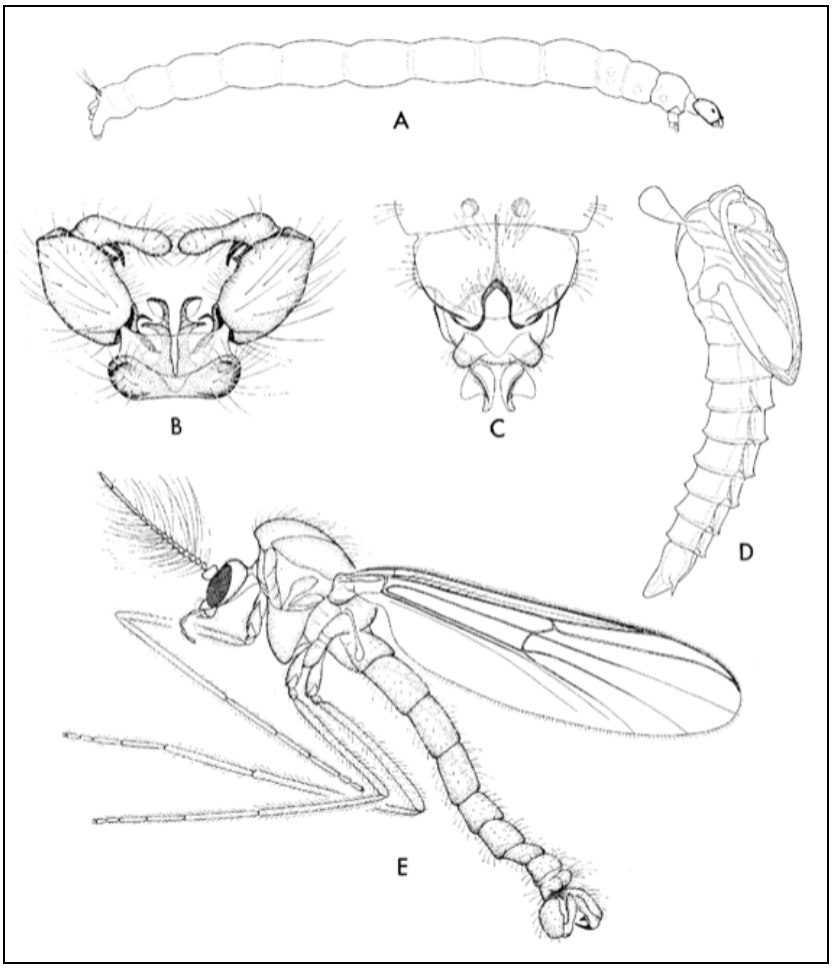

Figure 7.3. Sketches of *Parochlus steinenii*. A = larva; B = genitalia of adult male; C = genitalia of adult female; D = pupa; E = adult male (Wirth and Gressitt, 1967).

Diatom sp. – Only one as yet unidentified species of diatom was observed to the size fractions used within this study. This centric species was predominately 50 µm in

diameter, though some reached 100 µm. The remains did not stain with the rose Bengal, appearing clear with structures in light brown (Fig. 7.5a girdle view and Fig. 7.5b valve view). Other, smaller diatoms occurred in the sediment but were not retained on the sieve. This diatom is possibly a member of the genus *Cyclotella* which has been recorded in lake sediment cores from Hope Bay (Antarctic Peninsula) and from Potter Peninsula (King George Island) (Unrein *et al*., 2005).

Cosmarium sp. – This palynomorph was predominately 100 µm in size and did not appear to stain with the rose Bengal. This remain was kidney-shaped with two symmetrical halves being joined by an isthmus. The walls of this remain were ornately sculptured. Most examples of this palynomorph were bright green, suggesting the presence of green chloroplast. Other examples are pink to red and others clear, displaying empty cells without chloroplast content. The morphologies of this remain suggest that it was the desmid *Cosmarium* sp. (Fig. 7.5c) (Bayer, 2005).

Palynomorph 1 – This unknown spherical palynomorph was small, 50-100 µm, and does not appear to have stained with the rose Bengal. The remain was opaque brown with a smooth membrane, with opaque white contents.

Palynomorph 2 – This unknown palynomorph type was small, between 50-100 µm. This remain was spherical with a very unusual surface membrane. There seems to be raised uneven portions of the membrane, making it look wrinkled in appearance. These remains did not stain with the rose Bengal, and were light to dark brown (Fig. 7.5d).

Palynomorph 3 – This palynomorph type was opaque white and non-spherical. This remain did not stain with the rose Bengal and was relatively small ~100 µm. Some of the membranes appear to be smooth, whilst others seem to have a pitted surface (Fig. 7.5e).

Palynomorph 4 – This unknown palynomorph type appears to be very similar to the morphologies described for Palynomorph 3. The main difference is that these

remains tend to be larger, 100-200 µm, and all samples examined displayed pitted membranes. No examples of smooth membranes were identified as seen in palynomorph type 3 (Fig. 7.5f).

Palynomorph 5 – This unknown palynomorph type was similar in morphology to palynomorph type 4. These remains were 100-200 µm in size, and did not stain with the rose Bengal, appearing as a light brown. The membrane surface is also pitted like Palynomorph 4.

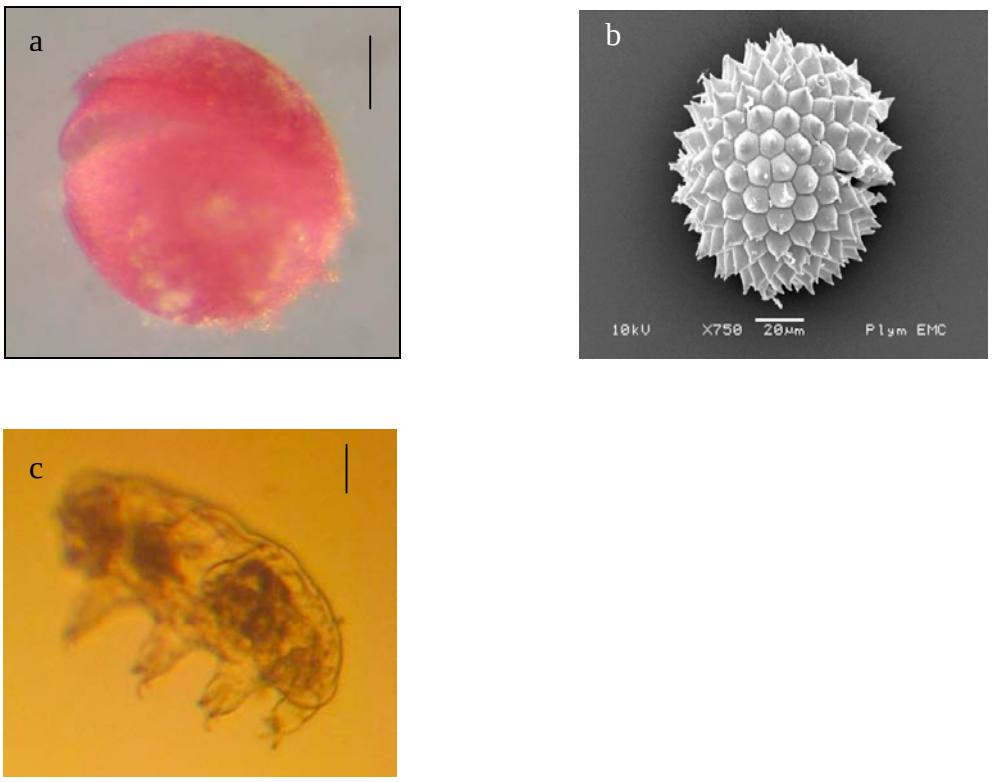

Figure 7.2. a) *Branchinecta gainii* egg. Scale bar represents 200 µm. b) *Dactylobiotus* cf. *ambiguus* egg. Scale bar represents 20 µm. c) Tardigrade, adult. Scale bar represents 100 µm.

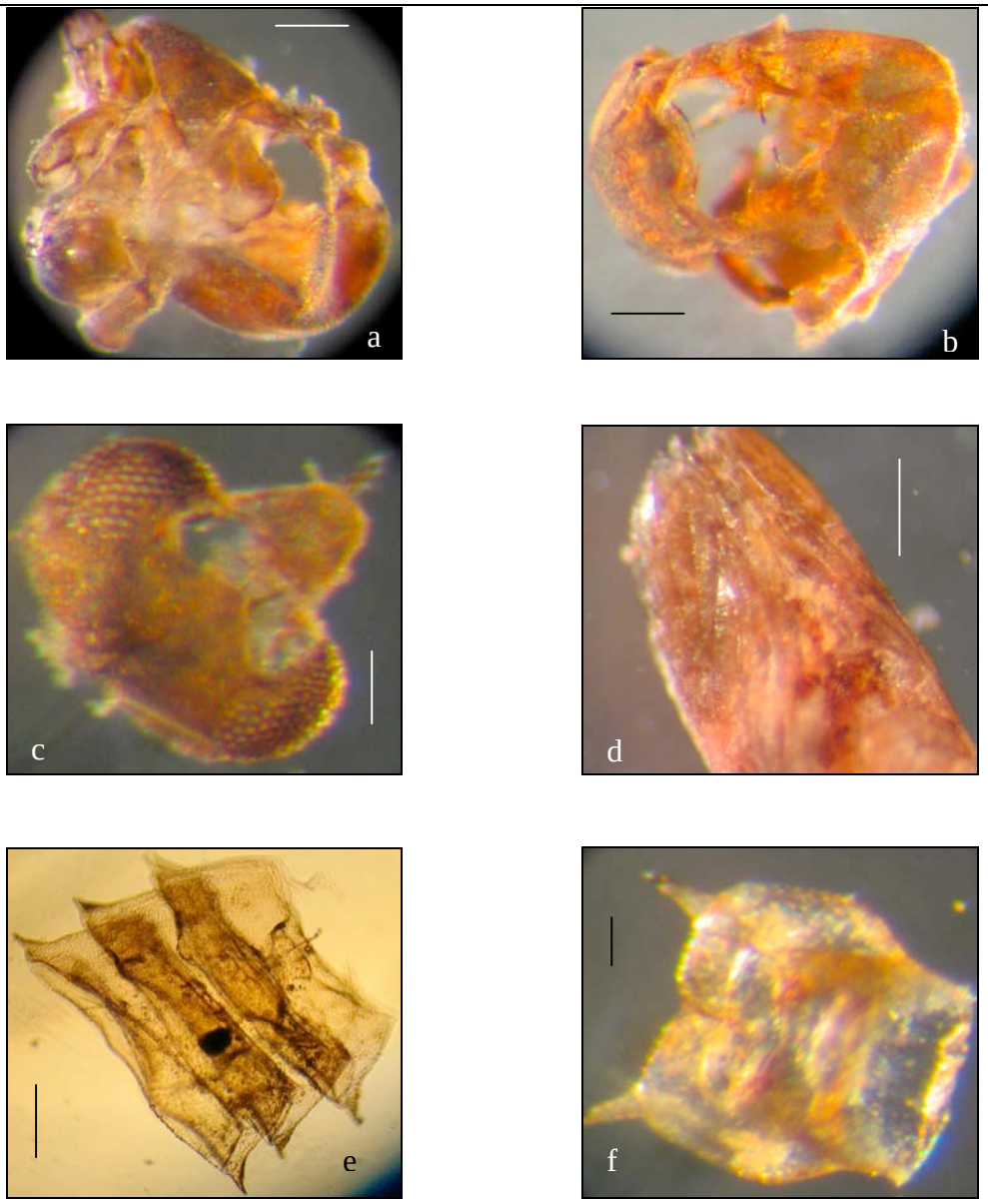

Figure 7.4. a) *Parochlus steinenii*. Thorax of adult. Scale bar represents 20 µm. b) *Parochlus steinenii*. Adult male. Scale bar represents 20 µm. c) *Parochlus steinenii*. Head capsule and compound eyes. Scale bar represents 20 µm. d) *Parochlus steinenii*. Wings and legs of pupa. Scale bar represents 50 µm. e) *Parochlus steinenii*. Pupa segments with laterally protruding spinelike processes. Scale bar represents 20 µm. f) *Parochlus steinenii*. Tail of pupa. Scale bar represents 20 µm.

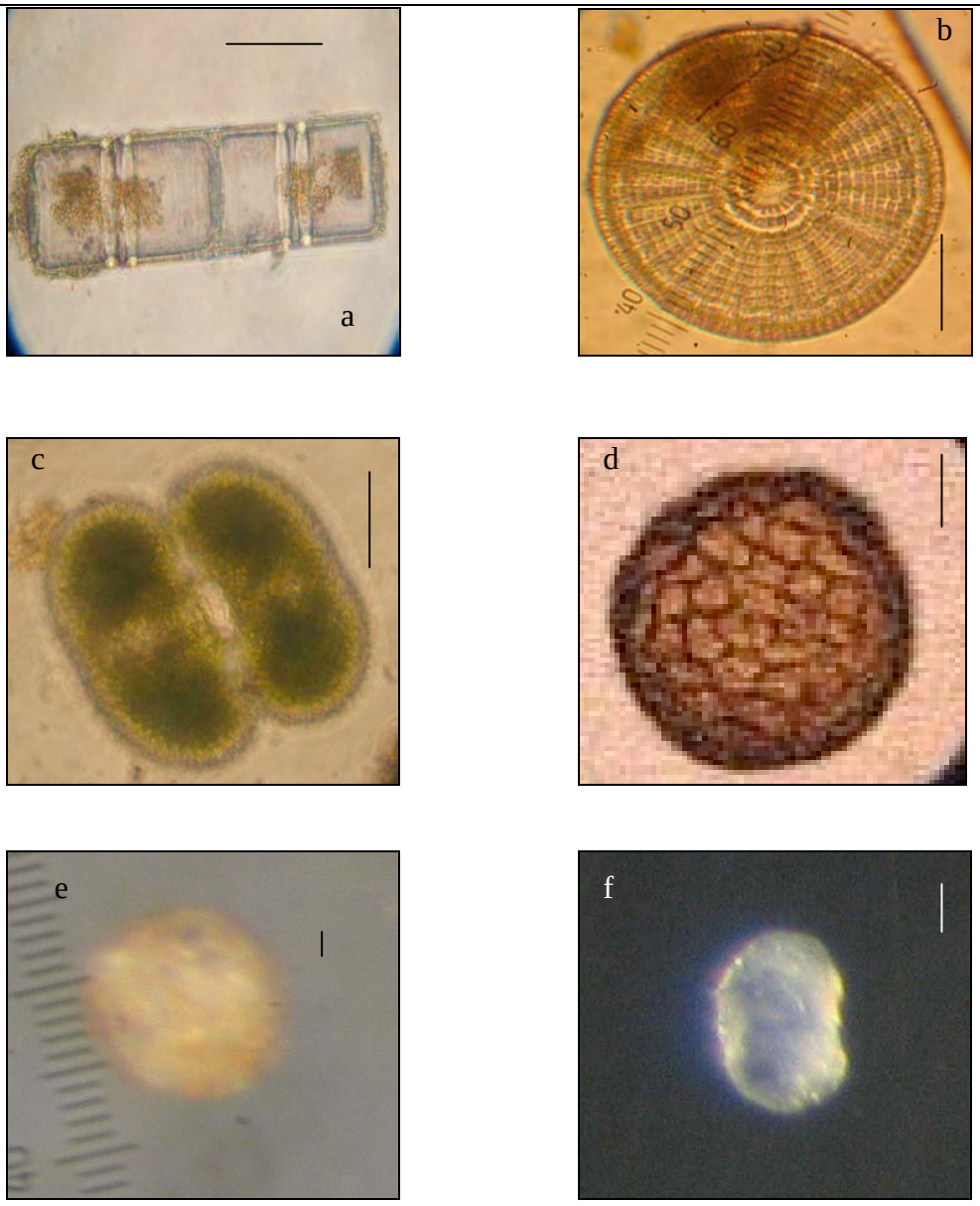

Figure 7.5. a) Diatom sp. Girdle view. Scale bar represents 20 µm. b) Diatom sp. Valve view. Scale bar represents 20 µm. c) *Cosmarium* sp. Scale bar represents 20 µm. d) Palynomorph 2, unknown. Scale bar represents 20 µm. e) Palynomorph 3, unknown. Scale bar represents 20 µm. f) Palynomorph 4, unknown. Scale bar represents 20 µm.

7.2 Stratigraphical analysis

The stratigraphical analyses shows that there was relatively low abundance of all organisms from 250-2110 yrs BP (Fig. 7.6). *Parochlus steinenii* tend to dominate during this time period with several peaks in abundance levels at 525 yrs BP; 600 yrs BP; 670 yrs BP; 1500 yrs BP; and 1700 yrs BP. There was a dramatic drop in the abundance of biota from 750-840 yrs BP, with <10 g_{dm}^{-1} *Dactylobiotus* cf. *ambiguus* eggs during this period. Abundance level of biota increases from 0-250 yrs BP with the biota being dominated by *Dactylobiotus* cf. *ambiguus*, *Cosmarium* sp., and Palynomorphs 2, 3, and 5. CONISS analysis showed a marked change in community situated at 13 cm (Fig. 7.6; Appendix 2).

The abundance of moss remains was crudely evaluated upon a macro-visual 1-5 scaling of abundance. It can be seen that high moss abundances occur from 1000-2100 yrs BP, with extremely high peaks at 1100 and 1200 yrs BP. There was a dramatic drop in moss abundances from 0-1000 yrs BP with slight increases at 200 and 550 yrs BP.

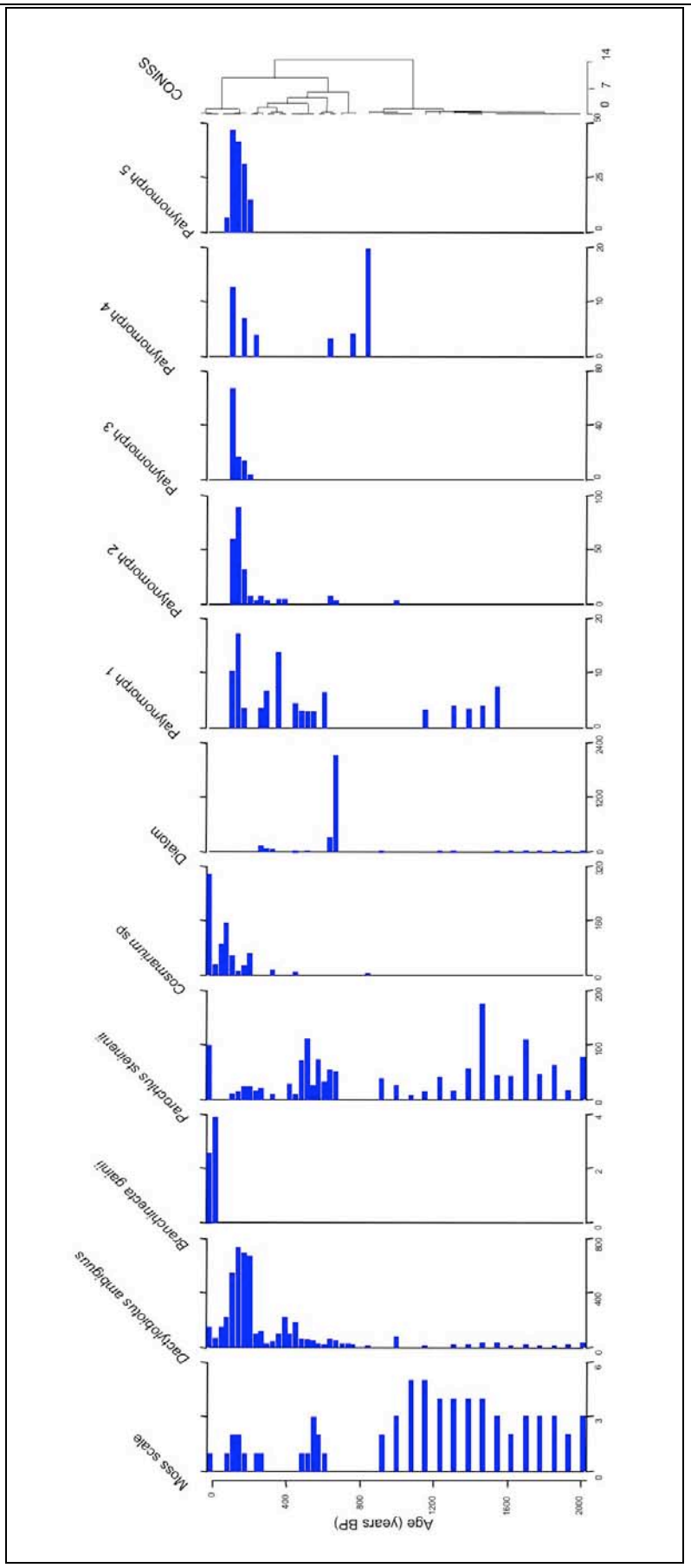

Figure 7.6. Stratigraphical analyses of Limnopolar Lake sediment core and CONISS cluster analyses.

Chapter Eight

DISCUSSION

8 Introduction

This chapter discusses the characteristics of tephra in the sediment of Limnopolar Lake, including abundances, shard morphology and size, and composition. The possible volcanic sources for the tephra and stratigraphical correlations with other tephra horizons in the local area are given. Overall trends in the lake biota in terms of apparent responses to tephral input are presented. Eight distinct communities are identified and possible reasons for shifts between these communities are discussed.

8.1 Tephra abundance

Tephra from major volcanic events have been deposited in Limnopolar Lake every 200-300 years over the last ~2000 years: with Horizon 1 being deposited at ~1600 years BP; Horizon 2 at ~1250 years BP; Horizon 3 at ~1020 years BP; Horizon 4 at ~300 years BP; and Horizon 5 at ~220 years BP (assuming a linear sedimentation rate). The exception is an apparent gap in tephral input between 1000-500 years BP (Fig. 8.1). This period may have been a time of relative volcanic quiescence, or may have been a period when wind patterns were not ideal for the transport of tephra into Limnopolar Lake.

Background levels of tephra occur within lake sediments as a result of the deposition of tephra across the local watershed. This tephra can then be washed into the lake via surface runoff. Assuming a sufficient surface water flow, this secondary deposition of tephra will provide constant input into the lake until the tephra resources have been depleted from the catchment area. During periods of high precipitation, or

meltwater from glaciers, larger tephra shards will be transported to the lake due to greater flow velocities providing more energy for transportation. Additionally, tephra that has been washed into the lake may differ in morphology and composition due to erosional processes and ionic leaching of the tephra prior to secondary deposition into the lake (Abella, 1988; Björck *et al.*, 1993).

From 750-2100 years BP a tephra background level in the Limnopolar Lake sediment was approximately 25,000 g_{dm}^{-1}, rising to ~ 30,000 g_{dm}^{-1} after 500 years BP. This change in tephra background occurred after a 500-year gap when there was little volcanic input into the lake. This change in background levels may be attributable to the dynamic landscape of Byers Peninsula resulting in an alteration of local hydrology after this dry period. Additionally, the finer shard sizes during this time may indicate a lower flow of water.

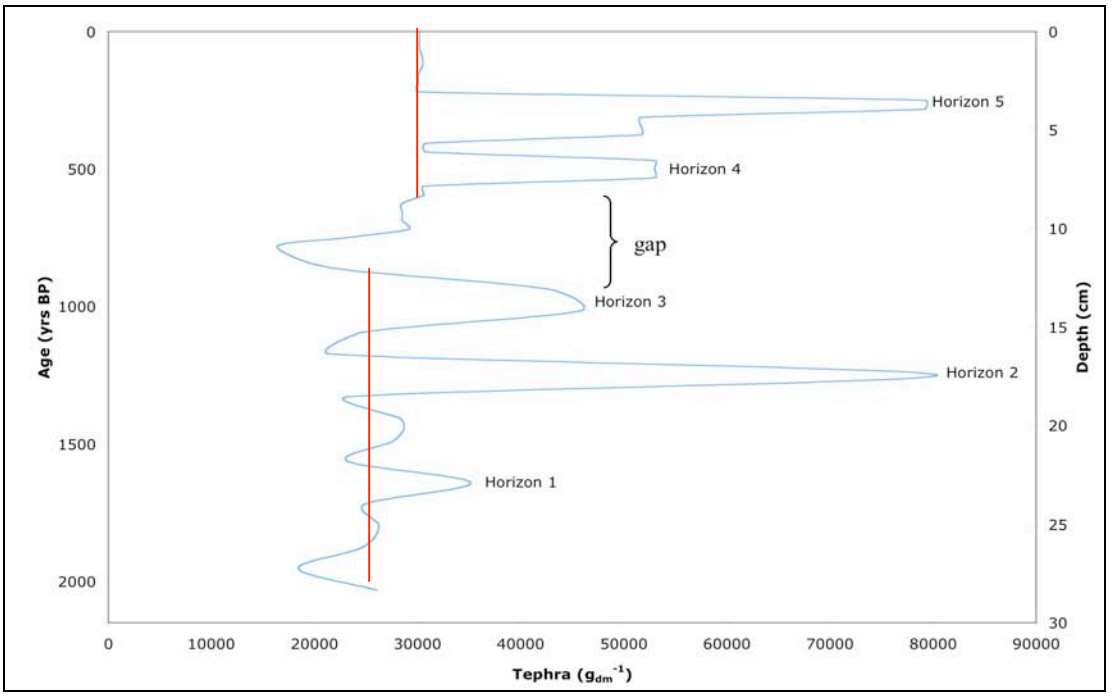

Figure 8.1. Age and depth of tephra within sediment from Limnopolar Lake. The 500-year gap with no volcanic input is highlighted by a brace, with the red lines indicating the differing background levels of tephra.

As tephra grain size appears to increase with greater tephra loadings, it could be argued that the large peaks in tephra may be a result of a wetter climate producing greater secondary inputs of larger grained tephra into the lake from the lake basin. However, the presence of consistent background levels and the lack of morphological

and compositional variation of the tephra suggest that the peaks were a result of individual volcanic eruptions.

Tephra shard size, morphology, and chemistry are now examined to determine possible volcanic sources and tephrostratigraphic correlations within the local region. These characterisations are utilised as ejected volcanic material is similar in composition to the source and tephra from particular eruptions produce shards with almost identical compositions and physical attributes.

8.2 Tephra shard morphology and shard size

Similar tephra shard morphologies to those observed from Limnopolar Lake have been identified in ice and lake sediment cores from various locations on Livingston Island (Hodgson *et al.*, 1998; Pallàs *et al*., 2001); Signy Island (Hodgson *et al*., 1998); and from the central Bransfield Basin (Fretzdorff and Smellie, 2002). Shard morphologies from Livingston Island ice cores were predominately blocky, non-vesicular to moderately vesicular fragments with the presence of some moderate to highly vesicular pumice and fragments with broken fluidal surfaces (Pallàs *et al*., 2001). Shards from the Bransfield Basin were also found to be blocky with low vesicle content, with some shards being nearly vesicle free. Some typical pumice particles were also identified (Fretzdorff and Smellie, 2002). Shard morphologies identified from sediment cores from Sombre and Midge Lakes were predominately platy and non-vesicular (Hodgson *et al.*, 1998). The predominant shard morphology in Limnopolar Lake was angular to blocky, with low to moderate vesicle contents. The similarity of Limnopolar Lake tephra to the above mentioned nearby tephra deposits suggests a common source.

Variations in tephra size distributions and morphologies are a likely product of the distance from the source volcano and secondary aerological and catchment sorting processes (Hodgson *et al*., 1998). Smaller tephra shards are most likely derived from volcanic sources located at further distances than those creating larger sized shards. The rare presence of partial fluidal surfaces of some tephra shards suggests that they

were temporarily isolated from quenching mechanisms during possible phreatomagmatic eruptions (Pallàs *et al*., 2001).

8.3 Composition and volcanic sources of tephra

The predominant silica content of the tephra shards was between 52-63 wt%, indicating that the shards were basaltic andesite to andesite in composition. Few tephra shards had silica contents between 48-52 wt%, suggesting some basaltic tephra have been deposited. Higher total alkali content of some tephra shards represents the deposition of trachy-basalt and basaltic trachy-andesite shards into the lake.

By comparing the compositions of tephra shards with bulk compositions of volcanic centres across the Antarctic region, possible volcanic sources for the Limnopolar Lake tephra can be identified. Data on Holocene volcanic centres from the Antarctic was retrieved from the literature to compare with the tephra compositions of Limnopolar Lake. From these comparisons, it was clear that volcanic sources for the tephra in Limnopolar Lake were most likely within the South Shetland Islands (Figs. 8.2-8.6, all other data comparisons from around the Antarctic can be found in Appendix 3 as they have poor correlations with Limnopolar Lake tephra and are less relevant). Although Deception Island magma appeared to correlate well with the tephra identified from Limnopolar Lake, it cannot be unequivocally designated as the source, as volcanic compositions from Bridgeman and Penguin Islands are also very similar to some Limnopolar Lake tephra. Furthermore, the scatter of FeO in Limnopolar Lake tephra away from Deception Island FeO levels (Fig. 8.4) provides further evidence that Deception Island may not be the source. As no FeO data for Bridgeman and Penguin Islands were available, no direct comparison of FeO levels could be made for these possible sources. However, the majority of the total alkali and magnesium contents of Limnopolar Lake tephra (Fig. 8.2 and 8.3) were closer to Deception Island than Bridgeman and Penguin Islands.

Phreatomagmatic eruptions are common on Deception Island as it is a back-arc stratovolcano with a sunken flooded caldera (Smellie *et al.*, 1996; Ibanez *et al.*,

2003). Phreatomagmatic eruptions are likely to produce large quantities of fine ash that then have the potential to be transported several tens of kilometres from the source vent (Matthies *et al*., 1988; Pallàs *et al*., 2001; Smellie, 2002b). Eruptions from Deception Island therefore, have the potential to produce a sufficient amount of ejected volcanic tephra that could easily be transported to Byers Peninsula.

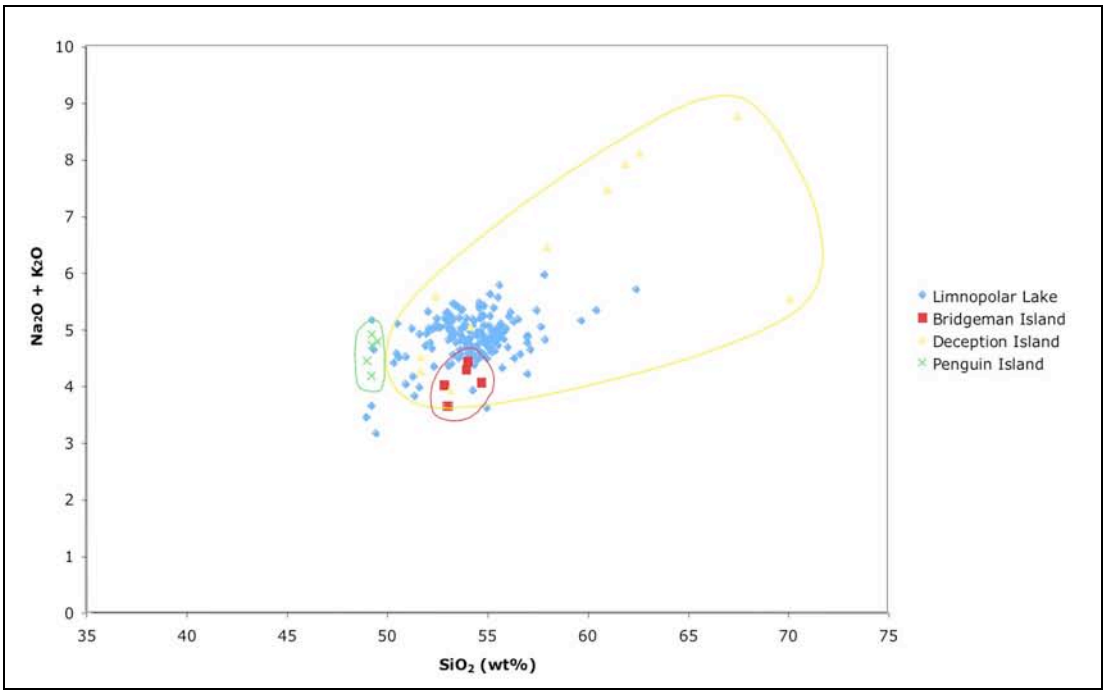

Figure 8.2. Sum of Na_2O and K_2O vs. SiO_2 for Holocene volcanic rocks from the South Shetland Islands and for Limnopolar Lake tephra shards (all bulk rock analyses extracted from various sources in LeMasurier and Thomson, 1990). Limnopolar Lake tephra has a very close relationship with Deception Island volcanic rocks.

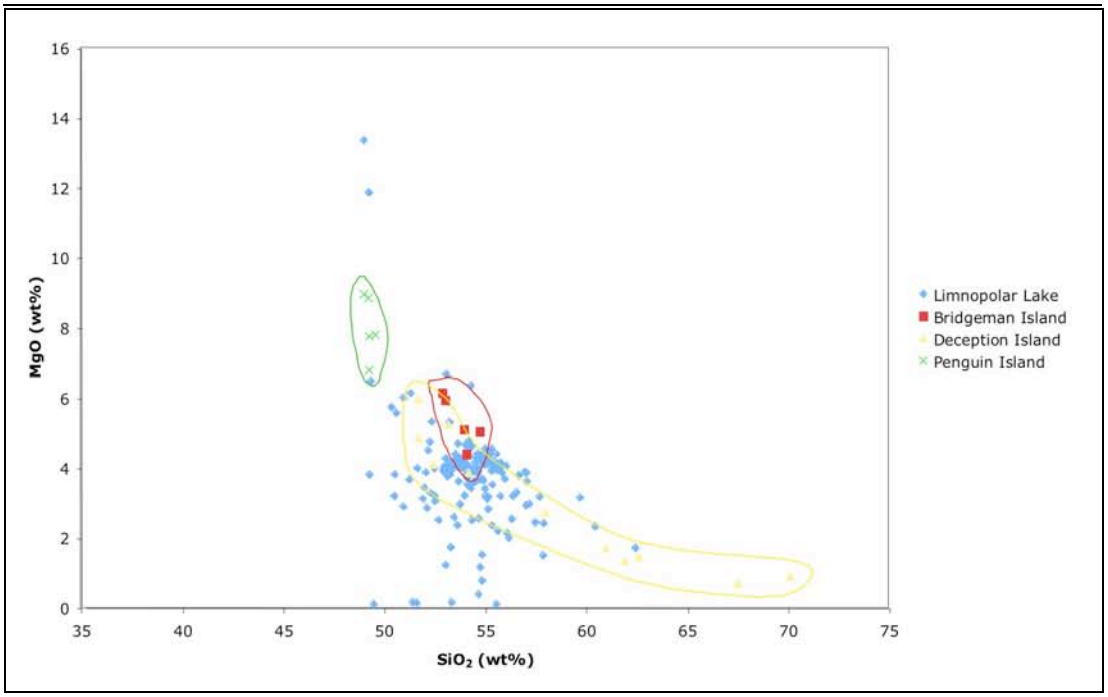

Figure 8.3. MgO vs. SiO_2 for Holocene volcanic rocks from the South Shetland Islands and for Limnopolar Lake tephra shards (all bulk rock analyses extracted from various sources in LeMasurier and Thomson, 1990).

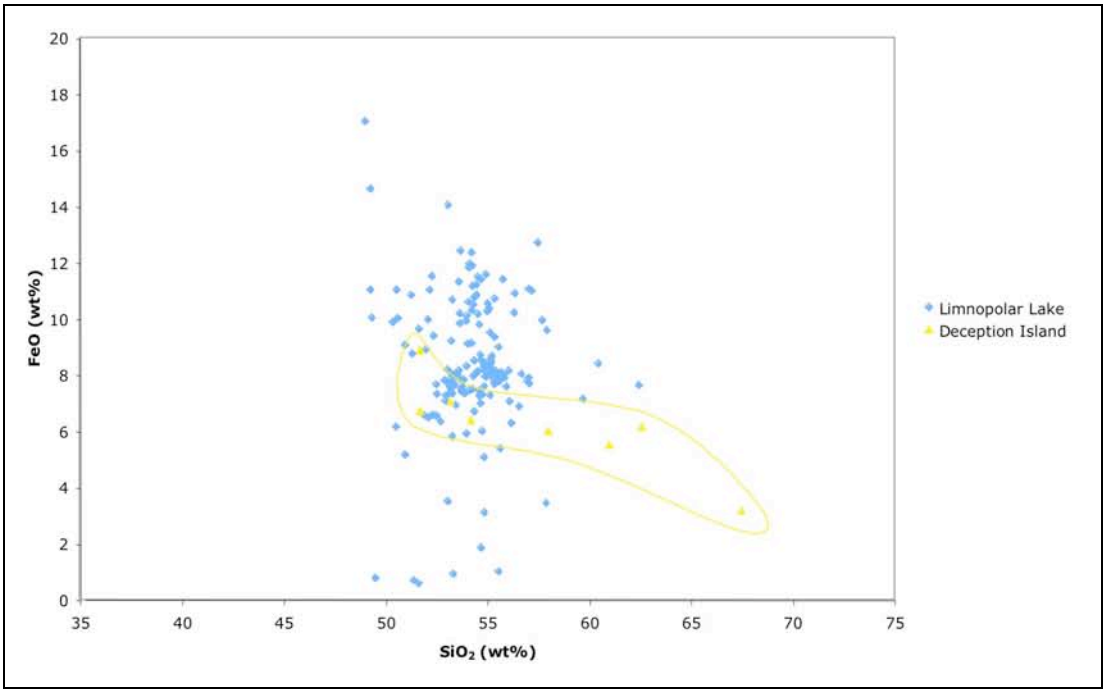

Figure 8.4. FeO vs. SiO_2 for Holocene volcanic rocks from the South Shetland Islands and for Limnopolar Lake tephra shards (all bulk rock analyses extracted from various sources in LeMasurier and Thomson, 1990).

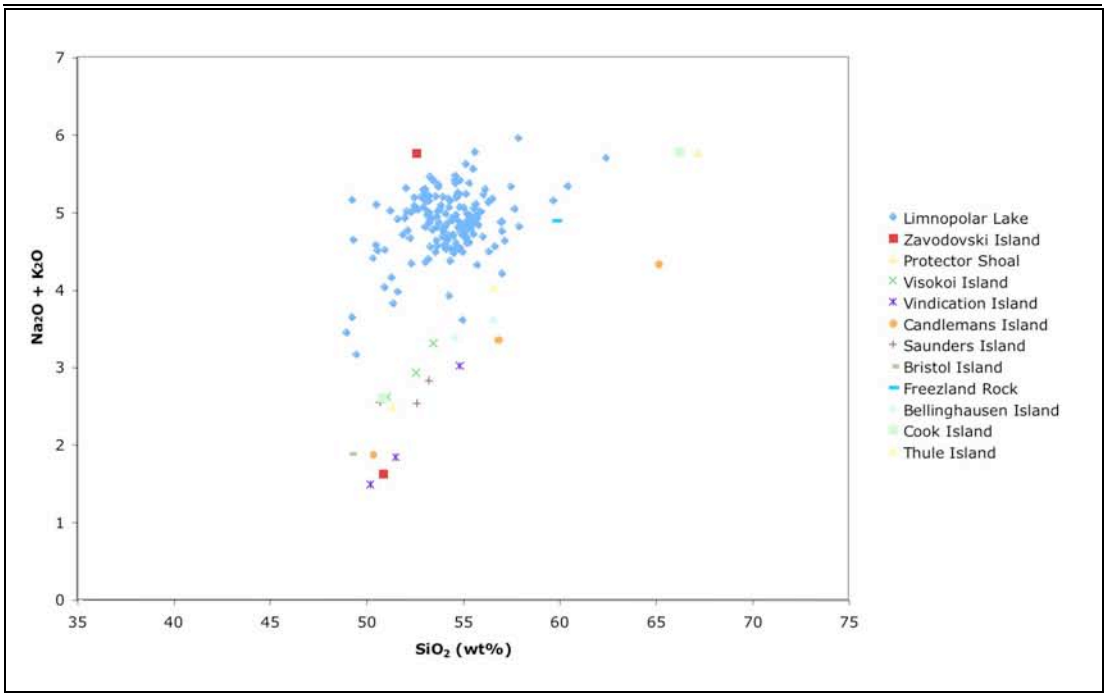

Figure 8.5. Sum of Na_2O and K_2O vs. SiO_2 for Holocene volcanic rocks from the South Sandwich Islands and for Limnopolar Lake tephra shards (all bulk rock analyses extracted from various sources in LeMasurier and Thomson, 1990).

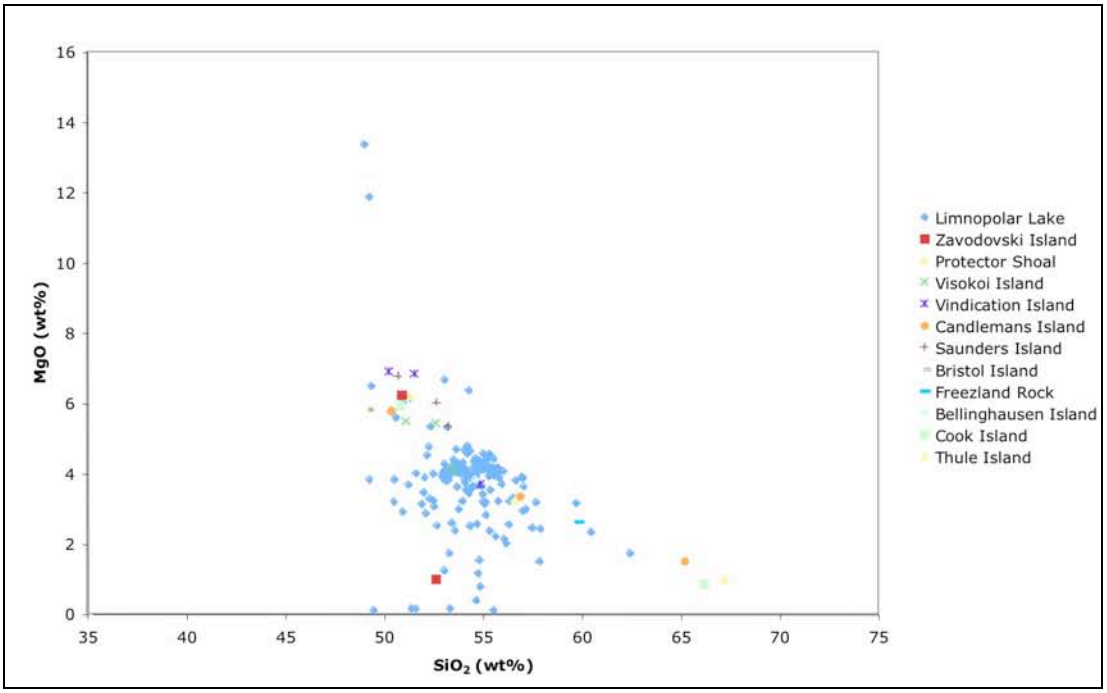

Figure 8.6. MgO vs. SiO_2 for Holocene volcanic rocks from the South Sandwich Islands and for Limnopolar Lake tephra shards (all bulk rock analyses extracted from various sources in LeMasurier and Thomson, 1990).

The composition of the tephra shards from Limnopolar Lake (Table 8.1) fell into the same ranges as three tephra horizons (TPH1; TPH2; and TPH3) identified by Pallàs *et al*. (2001) (Table 8.2); tephra from Midge Lake identified by Hodgson *et al*. (1998) (Table 8.3); and three tephra horizons (AP2; AP3; and AP5) identified from Björck *et al*. (1991d) from sites across the Antarctic Peninsula (Table 8.4).

Horizon 1 tephra from Limnopolar Lake are strongly correlated with tephra horizons AP3 and AP5, however there is a slight variation in the MgO (~2%) and CaO (~6%) contents. Horizon 2 strongly correlates with TPH3, Midge Lake 8-9 cm, and to a lesser extent with Midge Lake 21-22 cm, with a 2-3% variation in SiO_2 content. Horizon 3 strongly correlates with Midge Lake 3-4 cm, and to a lesser extent with TPH2, with a FeO variation of ~2%. Horizon 4 is similar in composition to TPH1, with horizon 4 being slightly (~1.5%) lower in FeO and slightly (~2%) higher in CaO. Horizon 5 appears to correlate with AP2, though horizon 5 is higher in CaO (~4%) and slightly (~2%) higher in MgO and CaO. These correlations are discussed in more detail in Section 8.4.

Table 8.1. Composition of tephra horizons from Limnopolar Lake (wt%). Horizons were identified on a depth basis, with Horizon 1 representing the first horizon into the lake, and Horizon 5 representing the most recent horizon.

	Horizon 1 (22 cm)	Horizon 2 (17 cm)	Horizon 3 (13-14 cm)	Horizon 4 (6 cm)	Horizon 5 (3 cm)
SiO_2	51.16%	54.45%	55.91%	56.08%	55.18%
TiO_2	2.22%	2.14%	1.56%	1.63%	1.59%
Al_2O_3	15.61%	15.43%	17.25%	16.65%	17.19%
FeO	10.13%	10.00%	7.76%	7.72%	8.26%
MnO	0.21%	0.19%	0.17%	0.21%	0.18%
MgO	5.64%	4.25%	4.03%	4.27%	4.30%
CaO	10.10%	8.47%	8.14%	7.99%	8.48%
Na_2O	3.96%	4.09%	4.22%	4.46%	3.95%
K_2O	0.59%	0.63%	0.65%	0.69%	0.60%

Table 8.2. Composition of tephra horizons TPH1, TPH2, and TPH3 from Livingston Island ice cores (wt%) (Pallàs *et al*., 2001). TPH3 was the deepest layer.

	TPH3	TPH2	TPH1
SiO_2	54.07% ±0.26	55.62% ±0.24	56.63% ±0.33
TiO_2	1.94% ±0.06	2.08% ±0.00	1.82% ±0.01
Al_2O_3	16.39% ±0.21	16.04% ±0.01	16.44% ±0.25
FeO	10.32% ±0.21	10.41% ±0.00	9.23% ±0.07
MnO	0.17% ±0.00	0.18% ±0.00	0.17% ±0.00
MgO	4.30% ±0.12	3.59% ±0.04	3.27% ±0.05
CaO	8.26% ±0.28	7.1% ±0.06	6.43% ±0.12
Na_2O	4.48% ±0.09	4.81% ±0.09	5.10% ±0.13
K_2O	0.62% ±0.04	0.77% ±0.04	0.89% ±0.02

Table 8.3. Composition of tephra horizons from Midge Lake (wt%) (Hodgson *et al*., 1998).

	Horizon 21-22 cm	Horizon 8-9 cm	Horizon 3-4 cm
SiO_2	52.18 ±1.47	53.90 ±2.41	53.84 ±0.62
TiO_2	2.34 ±0.18	2.30 ±0.26	1.88 ±0.55
Al_2O_3	14.6 ±0.61	14.34 ±0.51	16.48 ±0.57
FeO	9.98 ±1.14	9.72 ±0.20	8.16 ±0.81
MnO	0.23 ±0.00	0.22 ±0.01	0.20 ±0.03
MgO	4.34 ±0.74	3.70 ±0.94	3.43 ±0.61
CaO	8.24 ±1.15	7.31 ±1.61	7.97 ±0.31
Na_2O	4.75 ±0.17	4.54 ±0.07	5.05 ±0.05
K_2O	0.62 ±0.21	0.77 ±0.26	0.65 ±0.12

Table 8.4. Composition of tephra horizons from Byers Peninsula (wt%) (Björck *et al*., 1991d). AP5 was the deepest layer.

	AP5	AP3	AP2
SiO_2	52.80% ±2.54	52.08% ±1.28	54.30%
TiO_2	1.28% ±0.27	1.75% ±0.14	1.39%
Al_2O_3	15.66% ±0.69	16.14% ±0.36	14.90%
FeO	9.36% ±2.27	10.04% ±0.31	8.84%
MnO	0.11% ±0.02	0.16% ±0.02	0.14%
MgO	3.08% ±0.73	3.87% ±0.20	2.71%
CaO	3.95% ±1.19	6.68% ±0.65	3.75%
Na_2O	2.39% ±0.61	3.71% ±0.43	2.53%
K_2O	0.97% ±0.22	0.74% ±0.07	0.92%

8.4 Tephrostratigraphy

There have been no methodical studies of tephra for the Antarctic Peninsula; existing named tephra layers are poorly described, resulting in the differentiation of multiple tephra layers being near impossible due to insufficient data (Smellie, 1999). This lack of data has hampered every tephra study that has taken place since studies began in 1972 (Roobol, 1973; Björck *et al.*, 1991a,b; Björck *et al.*, 1996; Hodgson *et al*., 1998; Smellie, 1999; Pallàs *et al.*, 2001; Fretzdorff and Smellie, 2002).

New tephra studies at various locations around the Antarctic Peninsula need to be carried out systematically and reported in a consistent manner. This approach will provide a robust tephrostratigraphy of the region that will make differentiation of tephra horizons easier. It will also prevent the same tephra horizon being re-named several times in different studies. Once a tephra horizon has been identified and labelled, it should keep this label in further and supplementary studies to aid in identification and avoid confusion.

Deception Island has repeatedly erupted basaltic andesite and andesite magmas with low potassium contents throughout its history (Matthies *et al*., 1988; Fretzdorff and Smellie, 2002), it is currently impossible to assign specific eruptive events to the tephra horizons recognised in many studies based solely on major oxide compositions. Therefore, any such correlations should be viewed critically.

The only possible tephrostratigraphic correlations involving Limnopolar Lake tephra is with three tephra horizons (AP2, AP3, and AP5) (Table 8.4) from Lakes 1, 2, and 35 on Byers Peninsula (Fig. 8.7, map Fig. 2.6) previously identified by Björck *et al*. (1991d). The only real discrepancy with this tephrostratigraphy correlation is an approximate 200-year age gap between the dates assigned to each tephra layer by Björck *et al*. (1991d) and radiocarbon dates obtained in this study, assuming a linear sedimentation rate (Table 8.5). However, it is stated that the dating of the tephra horizons by Björck *et al*. (1991b) are estimated radiocarbon ages only, but are more accurate than the assumed linear sedimentation rate applied in this study. It is therefore difficult to make undisputable assignments of horizon identity to the horizons in Limnopolar Lake. However, the radiocarbon model used in this study can be amended to enable tephrostratigraphic correlations (Fig. 8.8). Caution should be

applied when using this tephrostratigraphic model as some tephra horizons (AP3; AP5; AP10; and AP12) have been identified in multiple horizons at some localities, but this itself could be a distinguishing factor of tephra layers within this region (Smellie, 1999).

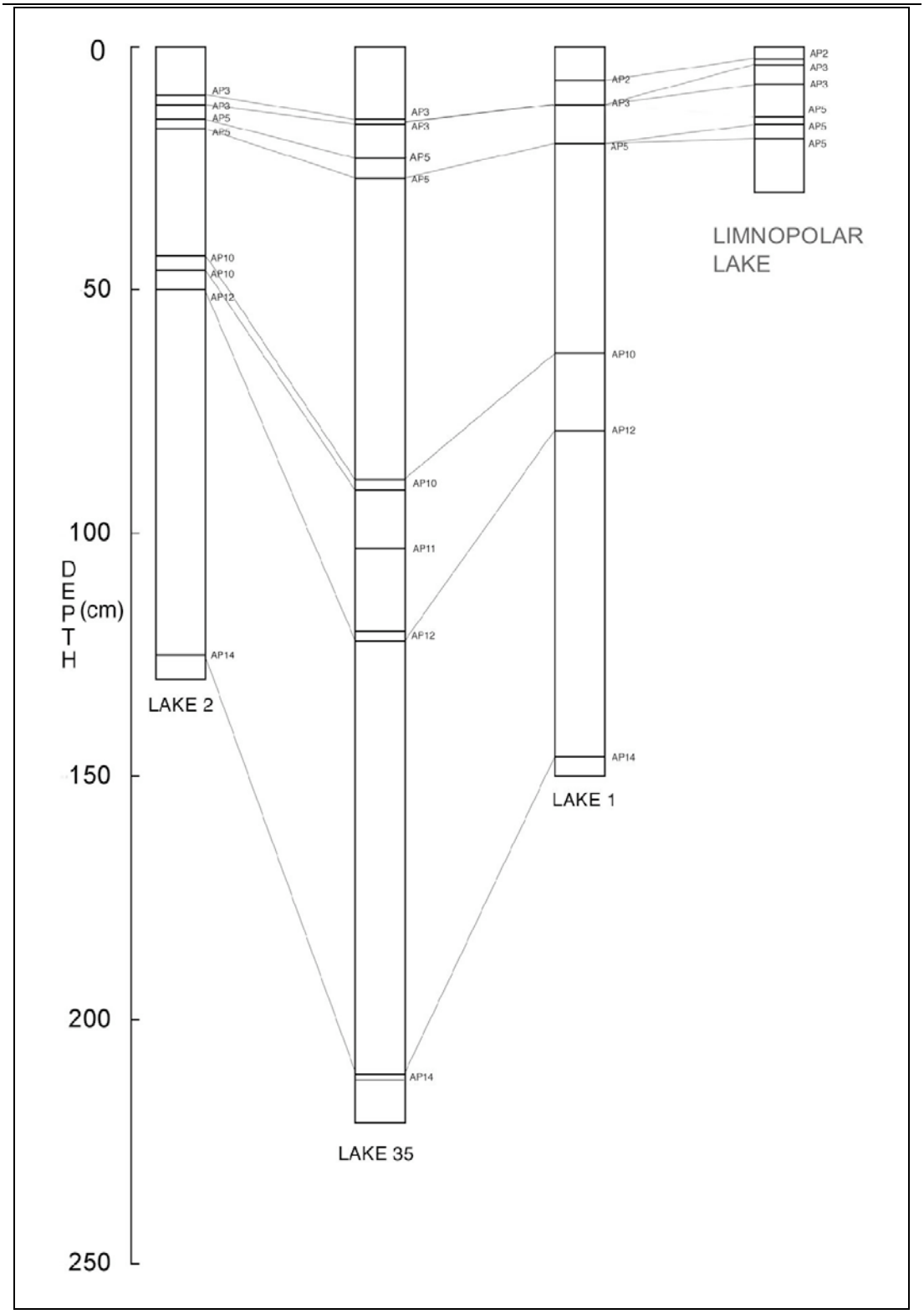

Figure 8.7. Tephrostratigraphic column for Byers Peninsula, Livingston Island. (Lake 1, 2, and 35 data extracted from Björck *et al*., 1991d).

Table 8.5. Radiocarbon age discrepancy for tephra horizons from Byers Peninsula.

Horizon	Age (Björck *et al.*, 1991)	Age (this study)
AP2	450 yrs	~200 yrs
AP3	750-800 yrs	300-600 yrs
AP5	1250-1400 yrs	1000-1400yrs

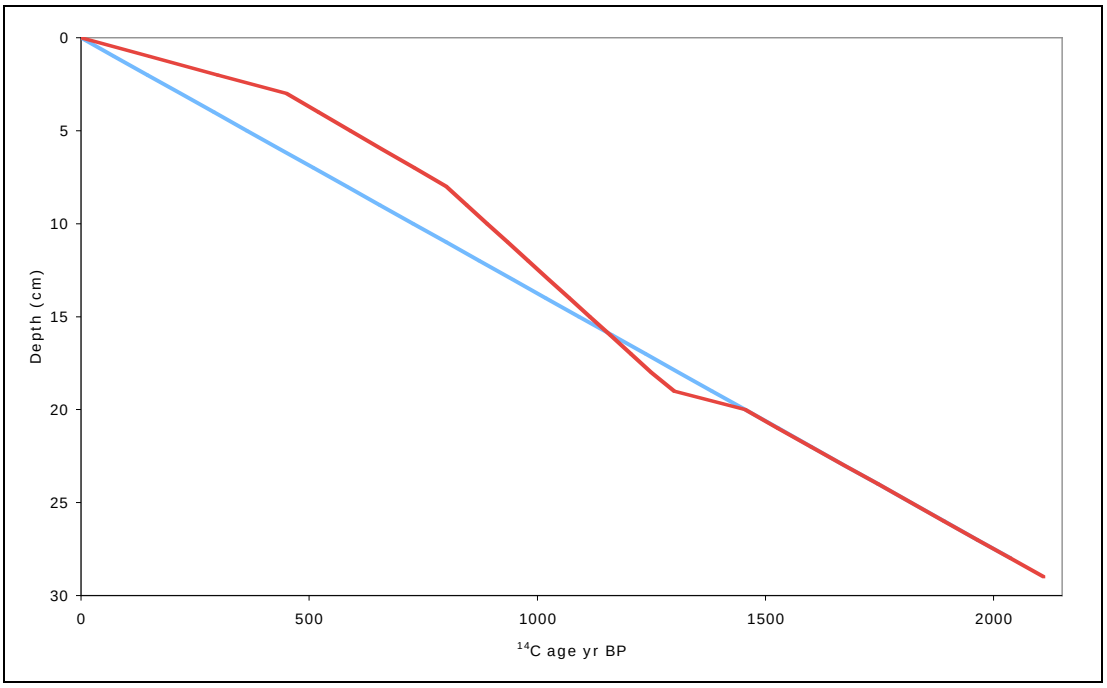

Figure 8.8. Blue line indicates the linear sedimentation applied in this study, the red line represents the amended sedimentation rate (Björck *et al.*, 1991d).

8.5 Overall trends in lake biota in terms of percentage organic carbon and carbonate

The percentage of organic carbon, as indicated by LOI_{550}, was low throughout the sediment core with values not exceeding 10%. For comparison, in Lake Boeckella (Hope Bay) and Ace Lake (Vestfold Hills). LOI_{550} was typically 15-45% (Cromer *et al.*, 2005; Gibson and Zale, 2006). A gradual decline in the percentage of organic carbon was recorded, with values dropping from 9-10% at the bottom of the core to approximately 4-5% in the most recent sediments (Fig. 8.9). A gradual decline in

LOI_{550} has also been identified in recent sediments from Lake Boeckella (Gibson and Zale, 2006), and Midge Lake, Livingston Island (Björck *et al.*, 1991a), suggesting that these changes in organic carbon are being recorded regionally. However, short-term minima of organic carbon may be attributable to dilution effects caused by the input of tephra into the lake during volcanic eruptions. For example, Gibson and Zale (2006) recorded very low LOI_{550} during periods of rapid tephral input into Lake Boeckella and concluded that this was attributable to tephra constituting a relatively greater percentage of the total sediment. There is no evidence of this happening in Limnopolar Lake.

There does not appear to be any consistent relationships between LOI_{550} and tephra abundance. There is however, an apparent correlation with LOI_{550} and moss abundance. LOI_{550} levels increase during periods of higher moss relative abundances from ~2100-900 years BP, and fall with decreasing moss relative abundances from 900 years BP to present. Grazing pressures may also influence apparent moss abundance levels. *Parochlus steinenii* abundances appear to correlate with the changes in LOI_{550}, but rather than this being a direct response to LOI_{550}, it may reflect an indirect relationship, as both are reliant on moss abundance.

The percentage carbonate, as indicated by $*LOI_{950}$, was fairly constant at approximately 2-3% from 2100 years BP to ~300 years BP. Carbonate values increased from approximately 300 years BP to present. There does not appear to be a direct relationship between the abundance of tephra or moss and $*LOI_{950}$ values. However, there is a stronger relationship between the percentage of carbonates and grazing biota within Limnopolar Lake. Higher biota abundances tend to occur in the same intervals as higher carbonate values. This response could be attributed to greater productivity in the lake producing higher pH levels resulting in precipitation of carbonate minerals (Dean, 1999; Cohen, 2003). It seems counterintuitive that higher productivity, as indicated by increased carbonates, is accompanied by low LOI_{550}. There was a significant shift in the nature of the organic carbon present away from moss at ~900 years BP, probably to cyanobacteria and algae. These are more accessible to grazers, and therefore more organic carbon was transferred to the grazing community. This is also reflected in the greater abundance of many of the animals later in the sediment record.

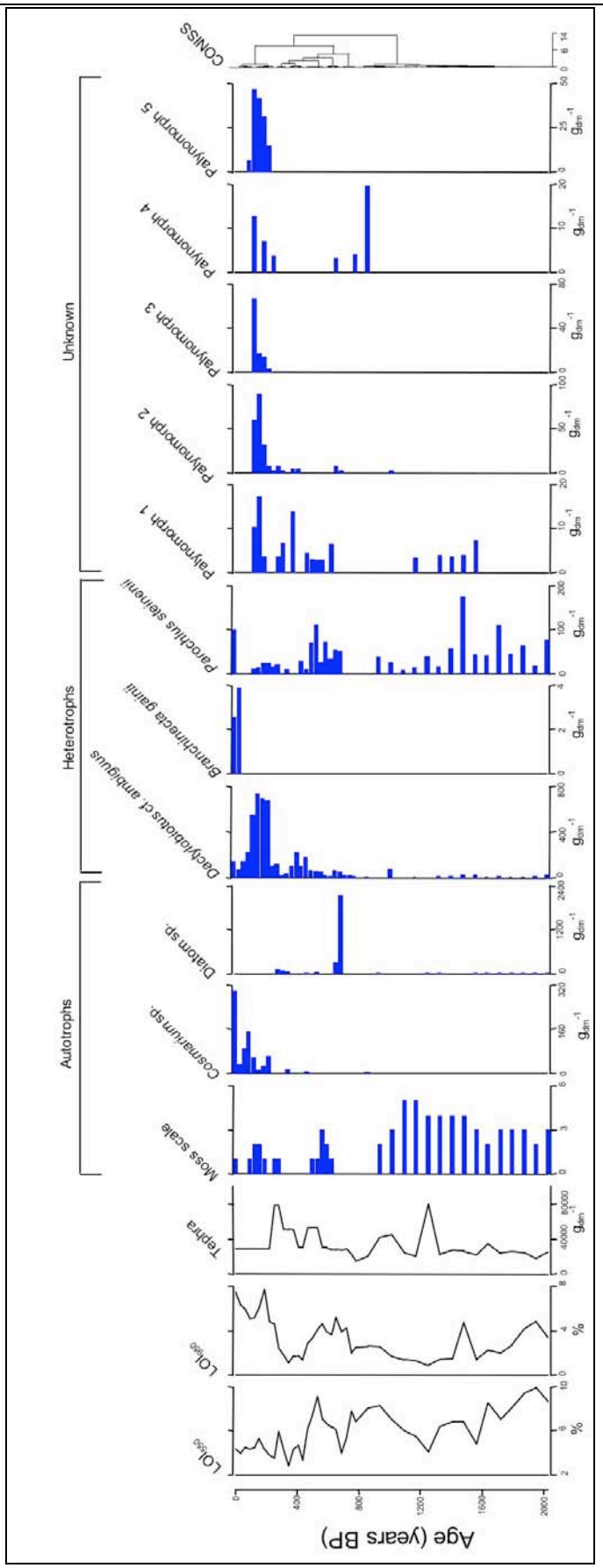

Figure 8.9. Stratigraphical analyses of biota including LOI_{550}, *LOI_{950}, tephra and CONISS cluster analyses. Relative abundance of moss was estimated on a scale of 0 (moss absent) to 5 (most abundant).

8.6 General biota and total abundances

The overall total abundance levels of the biota was relatively low (<100 g_{dm}^{-1}) from 2100 to ~600 years BP, and increased from ~600-250 years BP to values of approximately 300 g_{dm}^{-1}. Sediment deposited after ~250 years BP appears to be the most productive with total abundance of approximately 900 g_{dm}^{-1}. Total abundance dropped in most recent sediments to 500 g_{dm}^{-1}. However, the overall relative abundance levels of the biota cannot be interpreted as "true" abundance levels as some organisms may not have been preserved within the sediment record and decomposition profiles need to be considered for remains that have been partially preserved within the sediment. If decomposition were occurring in the sediment, an exponential drop in abundance with depth would be expected. *Dactylobiotus* cf. *ambiguus* eggs and *Branchinecta gainii* are known to be preserved in Antarctic Peninsula lake sediments for many thousands of years due to their resistance to bacterial and fungal breakdown (Björck *et al.*, 1996; Gibson and Zale, 2006). It can therefore be assumed that remains of *Dactylobiotus* cf. *ambiguus* eggs and *Branchinecta gainii* are indicative of relative abundance levels rather than representing decomposition profiles. Diatom sp. are also generally well preserved due to their siliceous frustules, and it is unlikely that any decomposition has occurred. *Parochlus steinenii* was recorded throughout the length of the sediment core (Fig. 8.9) and is well preserved due its sclerotised body parts. It can then be assumed that the abundance levels recorded for this species are not indicative of a decomposition profile. The relative abundance of Palynomorphs 1-5 may represent decomposition profiles, however it is difficult to confirm this possibility as the organisms remain unidentified, and therefore it is uncertain if these organisms have previously been identified within sediment cores from the Antarctic Peninsula, and assumptions cannot be made regarding preservation capabilities of the palynomorphs as the composition of these palynomorphs remain unknown.

Moss stems and leaves displaying etiolation occurred throughout the length of the core, suggesting that the moss had grown within the lake environment and is not a product of inwashing from the surrounding catchment area (Seppelt and Kanda, 1986). The apparent change from a moss-dominated ecosystem from 2100-950 years BP to a cyanobacterial and algal dominated ecosystem from 950 years BP to present was strongly supported by the two distinct groups within the CONISS cluster

analysis. The higher moss levels from 2100-950 years BP were indicative of low nutrient levels and low productivity within the lake environment (Heywood *et al.*, 1980). This shift in ecology may be due to higher nutrient inputs into the lake from the drainage basin. Extensive growth of aquatic moss has also been recorded in Lake Boeckella following inputs of tephra (Gibson and Zale, 2006).

8.7 General biotic responses to tephra inputs

The general abundance of biota within Limnopolar Lake tended to decline when tephra levels exceeded >30,000 g_{dm}^{-1}. Tephra counts of ~30,000 g_{dm}^{-1} were background levels caused by the continual inwashing of tephra from the surrounding watershed. It can therefore be assumed that organisms within Limnopolar Lake are adapted to tephra input of this magnitude.

Large tephra inputs, >30,000 g_{dm}^{-1}, appear to occur prior to ecosystem changes within Limnopolar Lake, as highlighted by the CONISS cluster analyses (Fig. 8.10). This could represent lake biota recovering, not necessarily into its same state, from stresses resulting from tephral input. Through examining the overall biota of the lake it can be seen that large tephra inputs (>50,000 g_{dm}^{-1}) tend to prevail within the lake system for approximately 50-150 years. After this time period lake biota abundance levels tend to increase substantially.

Moss growing in Limnopolar Lake does not appear to suffer any type of blanketing effect from large tephra inputs. This conclusion is drawn from the fact that moss levels remain high from ~1950-2100 years BP, a period of time in which one large tephra event (~80,000 g_{dm}^{-1}) and at least two smaller tephra events took place. *Parochlus steinenii*, the abundance of which is related to that of moss, remained abundant during large tephra inputs. However, tephra input has been shown to have an effect on chironomid populations. Studies carried out by Heinrichs *et al.* (1999) showed that changes in chironomid populations from Kilpoola, British Colombia were attributable to the increased ionic concentrations due to solutes derived from freshly deposited tephra from the Mount Mazama eruption. However, during the large tephra input from ~200-300 years BP there was a decrease in abundance of

Parochlus steinenii, suggesting that this response may have been triggered by a vector other than tephra input or through indirect impacts of tephra. For example, *Parochlus steinenii* abundance may have been affected by negative moss responses to tephra loadings driving this event.

Dactylobiotus cf. *ambiguus* eggs appear to have a strong response to deposition of tephra Horizons 4 and 5 into the lake. It can be seen that *Dactylobiotus* cf. *ambiguus* have adapted to surviving tephra levels from ~30,000-45,000 g_{dm}^{-1}, however, egg abundances of this species tend to decrease if the tephra input into the lake exceeds ~45,000 g_{dm}^{-1}. Following Horizon 4 and 5 inputs of tephra, *Dactylobiotus* cf. *ambiguus* egg remains appear to recover once tephra levels decrease below ~45,000 g_{dm}^{-1}.

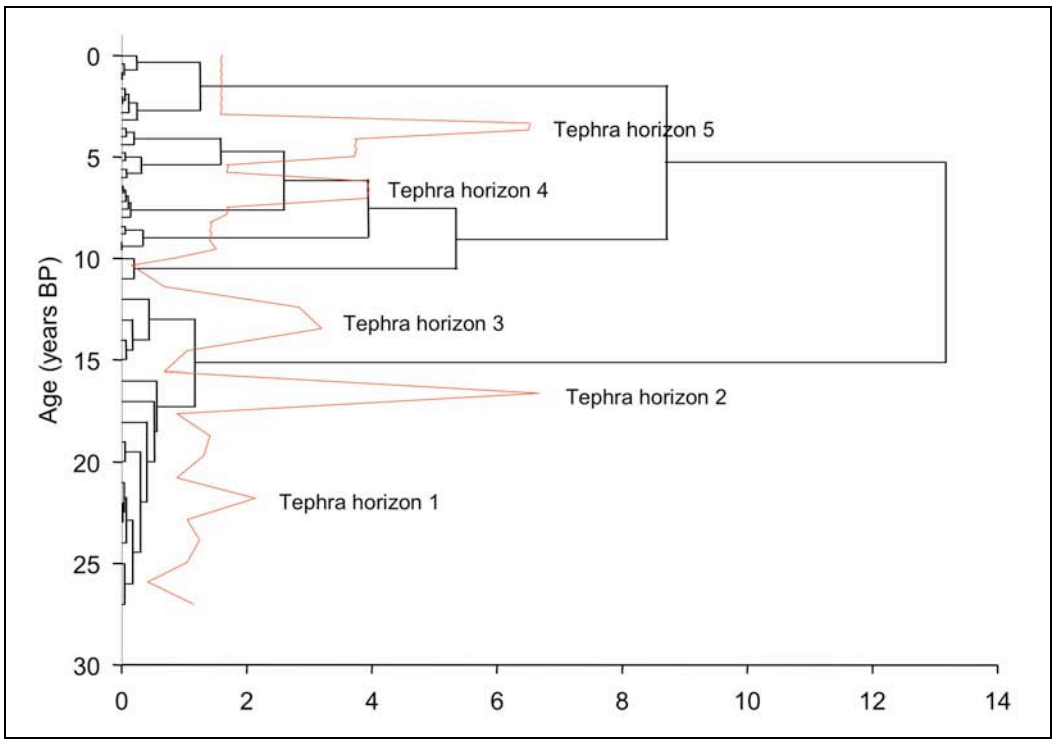

Figure 8.10. CONISS cluster analyses of biota in Limnopolar Lake sediment core with tephra count in red.

8.8 Apparent community changes

Stratigraphical analysis of all lake biota, LOI_{550}, $*LOI_{950}$ and abundance of tephra within the Limnopolar Lake sediment core, displays eight distinct communities

within the sediment (Fig. 8.11): Community 1 from ~2110-1600 years BP; Community 2 from ~1600-1100 years BP; Community 3 from ~1100-950 years BP; Community 4 from ~950-750 years BP, Community 5 from ~750-500 years BP; Community 6 from ~500-200 years BP; Community 7 from ~200-100 years BP; and Community 8 from ~100 years BP to present. Community 1 is the ecosystem present at the bottom of the sediment core.

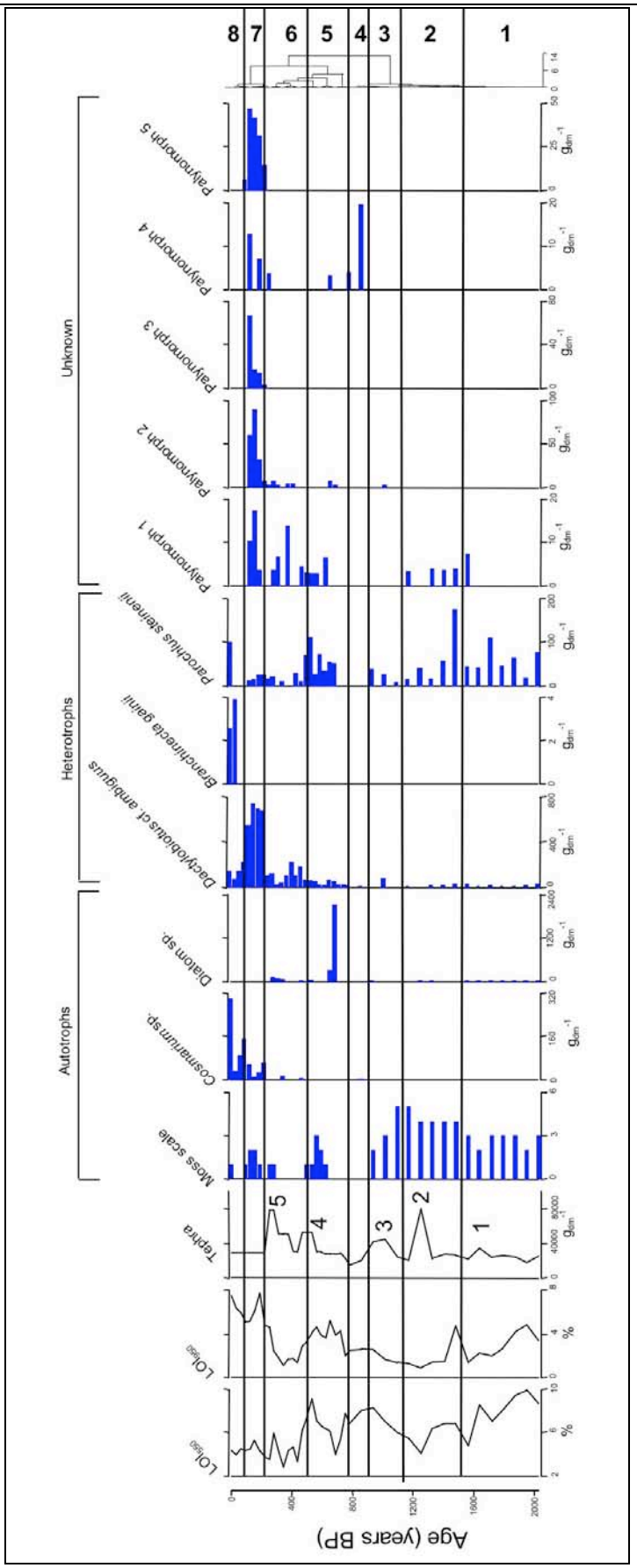

Figure 8.11. Stratigraphical analyses including LOI_{550}, $*LOI_{950}$, abundance of tephra and lake biota of Limnopolar Lake. Numbers 1-8 at top of figure represent numbered ecosystem changes. Numbers 1-5 of tephra represents horizons.

Community 1 (29-23 cm: ~2210-1600 years BP): High moss and *Parochlus steinenii* levels are apparent within this community, with low abundances of *Dactylobiotus* cf. *ambiguus* and Diatom sp. This ecosystem appears to change after the input of Horizon 1 tephra into the lake. Tephra abundances were at background levels <30,000 g_{dm}^{-1}. LOI_{550} and $*LOI_{950}$ decrease during this period.

Community 2 (23-14 cm: ~1600-1100 years BP): High abundance levels can be seen in moss and in the appearance of Palynomorph 1. *Parochlus steinenii* abundance levels decrease, but then increases abruptly at ~1500 years BP. Low abundance levels were recorded for *Dactylobiotus* cf. *ambiguus* and Diatom sp. Tephra abundance was slightly higher preceding the input of Horizon 2 tephra. LOI_{550} decreases substantially from levels observed in Community 1 and $*LOI_{950}$ decreases slightly with a sharp peak at approximately 1500 years BP.

Community 3 (14-13 cm: ~1100-950 years BP): The abundance of moss and *Parochlus steinenii* decrease and Palynomorph 1 appears to be absent from this community. There is a slight increase in *Dactylobiotus* cf. *ambiguus* at approximately 1000 years BP, which may have created the slightly lower moss levels during this time due to grazing pressures. Palynomorph 2 appears in this community with low abundances at approximately 1000 years BP. The tephra abundance was higher due to the input of Horizon 3 during this time. There was a substantial increase in the LOI_{550}, and a slight increase in $*LOI_{950}$.

Community 4 (13-10 cm: ~950-750 years BP): It appears that a catastrophic event to the lake biota occurred during this time. The community has reduced in overall productivity. Palynomorph 4 is present within this community at high abundance levels. The apparent disappearance of moss, *Parochlus steinenii*, Diatom sp. and Palynomorph 1 was recorded, as well as low abundance levels in *Dactylobiotus* cf. *ambiguus*. *Cosmarium* sp. also appeared briefly, at low abundance levels during this time period, suggesting low mineral loadings. Tephra abundances drop dramatically during this time, falling below the background level of ~30,000 g_{dm}^{-1}. LOI_{550} decreases slightly whilst $*LOI_{950}$ is fairly constant. This catastrophic event to lake biota cannot be attributed to tephra, as this time period is when tephra levels are lowest. The event may be explained by climate during this period. Studies carried out

by Björck *et al.* (1991a) on Livingston Island found that between 1500-500 years BP the region experienced a more continental climate making it colder and more arid. Ice advances were also identified to be taking place between 500-700 years BP, making this time a period with the harshest conditions for biological life to prevail over the last 2100 years (Zale and Karlen, 1989; Björck *et al.*, 1991a; Zale, 1994a). However, the effects of this climate change appears to be constrained to lake biota responses from ~950-750 years BP in Limnopolar Lake, though these dates must be viewed with caution due to the assumed linear sedimentation rate. This climate change may have several impacts on lake biota. For example, drier climates may increase salinity to levels above the thresholds of some organisms, and may also cause complete or partial drying out of the lake environment, and its surrounding catchment area. For example, tephra abundances falling below the background level may be attributed to these drier climatic conditions, as there would have been less precipitation and groundwater flow to transport tephra from the water catchment to Limnopolar Lake. Additionally, colder climates may lead to increased ice cover over the lake. This increased ice cover would decrease light penetration required for photosynthesis, resulting in an overall decrease in lake productivity (Quayle *et al.*, 2003).

Community 5 (10-7 cm: ~750-500 years BP): The most striking feature of this community is the large spike of Diatom sp. Singular diatom peaks have previously been recorded within Antarctic lake sediments, for example the lake peak of *Navicula cryptotenella* from sediment cores from lakes in the Windmill Islands, suggesting that this is not an uncommon occurrence within this region (Hodgson *et al.*, 2006). As this large diatom peak comes after the dramatic drop in biota abundance levels during 750-850 years BP, it may be attributable to a recovery and re-colonisation phase of the lake. *Parochlus steinenii* was recorded at high abundances and *Dactylobiotus* cf. *ambiguus*, Palynomorph 1, Palynomorph 2 and moss were at low abundances. Tephra increases during this time period, rising to approximately 60,000 g_{dm}^{-1} with the deposition of Horizon 4 tephra. There was an overall increase in LOI_{550} and $*LOI_{950}$.

Community 6 (7-3 cm: ~500-200 years BP): *Dactylobiotus* cf. *ambiguus* slightly increased in abundance, as did Palynomorph 1. *Cosmarium* sp., Diatom sp. and

Palynomorph 2 were recorded at low abundances. Tephra increased substantially to approximately 40,000 g_{dm}^{-1} and to 80,000 g_{dm}^{-1} with the deposition of Horizons 4 and 5. The deposition of Horizon 4 and 5 tephra may have caused a response in moss levels, as moss appears to be absent after the deposition of Horizon 4 tephra, with low abundances occurring prior to the deposition of Horizon 5 tephra. There was a substantial drop in LOI_{550} and a slight decrease in $*LOI_{950}$ from 500-300 years BP, increasing to ~8% at ~200 years BP.

Community 7 (3-2 cm: ~200-100 years BP): There was an increase in a wide range of biota during this period. *Dactylobiotus* cf. *ambiguus* increased and high abundance levels were also recorded in Palynomorphs 1-5. Tephra remained constant at a background level (~30,000 g_{dm}^{-1}). LOI_{550} remained fairly constant, whilst there was a slight decrease in $*LOI_{950}$. During this time it is evident that there has been no additional input of tephra into the lake. This could be a result of prevailing winds at the time of eruptions not having adequate strength to transport large tephra loads or not in ideal directions to transport tephra to Limnopolar Lake. The latter is exemplified by the absence of a tephra peak associated with 1967-1970 eruptions of Deception Island. The prevailing winds at the times of these eruptions carried the tephra away from Livingston Island (Fig. 8.12).

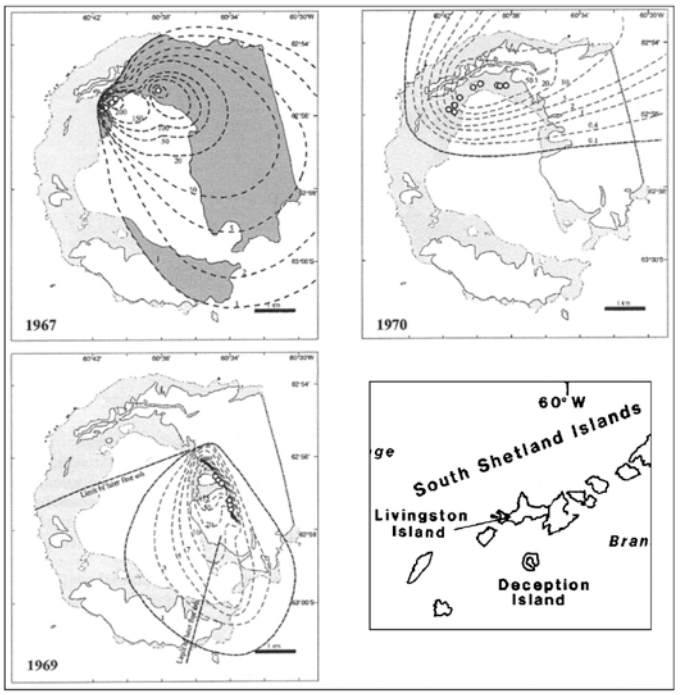

Figure 8.12. Sketch maps displaying the distribution and average thickness (cm) of ash falls from the 1967, 1969, and 1979 Deception Island eruptions (Smellie, 2002a). Inset map in bottom right hand corner displaying direction to Byers Peninsula (Smellie, 1990).

This theory is supported by the increased abundance of the desmid *Cosmarium* sp. during this time period. This species of algae is generally only present within lakes that experience low nutrient loadings (Ling and Seppelt, 1990; Spijkerman and Coesel, 1998). Therefore, the appearance of this species confirms that there was no new tephra input during this time and that nutrient levels had dropped substantially. This tephra stable time period has therefore provided the opportunity for many organisms to flourish.

Community 8 (2 cm-top of core: ~100 years BP to present): Sudden disappearances of Palynomorphs 1-5 and decreased abundances of *Dactylobiotus* cf. *ambiguus* suggested a major ecological shift. High productivity levels were recorded in *Cosmarium* sp., as well as in the first appearance of *Branchinecta gainii*. Studies carried out by Björck *et al*. (1996) on James Ross Island have identified long histories of preserved *Branchinecta gainii* eggs within lake sediment cores. This research suggests that the appearance of *Branchinecta gainii* eggs in the most recent sediment layers is indicative of recent successful colonisation of Limnopolar Lake. The apparent lack of other organisms in the most recent sediment layers may be attributed to the grazing pressures caused by this large benthic species in comparison with the size of other grazers within the lake. Another species that would be expected to preserve within the Limnopolar Lake sediment core was the copepod *Boeckella poppei*. This species has been recorded throughout lake sediment cores from the Antarctic Peninsula (Gibson and Zale, 2006). The cladoceran *Macrothrix* sp. has also been recorded within the current Limnopolar Lake environment, and may therefore be expected to be recorded within the sediment record (Rico *et al*., 2003). The apparent recent colonisation by *Branchinecta gainii*, and the absence of other species from the sediment such as copepods (*Boeckella poppei*) and cladocerans (*Macrothrix* sp.) suggests that these zooplankton species have only just begun to successfully colonise Limnopolar Lake. This may be a result of the substantial drop of tephra inputs into the lake providing a more stable environment that may be required for these zooplankton species to survive. Tephra abundances remained constant at a background level (~30,000 g_{dm}^{-1}). The percentage organics slightly decreased, whilst there was a dramatic increase in the percentage of carbonates.

The lake community in Limnopolar Lake has changed dramatically with time, and has been more variable over the last 1000 years BP. Community 1 was the base

community from the bottom of the sediment core and as a result, no assumptions can be made in regards to its composition. Changes from Communities 1, 2, 3, 5 and 6 appear to occur shortly after periods of high tephra input into the lake, which may suggest that long-term biotic responses may have a cumulative effect. Shifts from Communities 4 and 7 occur when tephra abundances within the lake are at their lowest. The shift in Community 4 may be a result of a colder and more arid climate, whilst the shifts from Community 7 may be attributed to competition and grazing pressures. The CONISS cluster analysis displays that Community shifts 1-4 (~0-950 years BP) are more extensive than within Community shifts 5-7 (~950-2100 years BP).

Tephra therefore, probably plays an important role in shaping Limnopolar Lake communities, however other variable such as climate variability, colonisation, and grazing pressures may also contribute to community compositions within the lake.

Chapter Nine

CONCLUSIONS

This project had two main goals: 1) to identify and characterise tephra horizons from Limnopolar Lake and to establish possible volcanic sources. Tephra could then be compared with other tephra horizons in the local region to establish if any tephrostratigraphic correlations could be made; 2) to identify possible lake biota responses to tephra input into the lake environment, through either direct or indirect affects, and to identify non-tephra related variables that may affect the composition of lake communities.

Limnopolar Lake has experienced an extensive volcanic history in the terms of the volcanic input of tephra into the lake and its surrounding catchment areas. Tephra abundances of <30,000 g_{dm}^{-1} were indicative of background levels caused by the continual washing in of tephra from the surrounding catchment area. Five tephral input horizons were identified throughout the length of the core, with tephra levels >30,000 g_{dm}^{-1}. This continual input of tephra and other factors has created substantial impacts on the lake environment and its ecology.

Chemical analysis of individual tephra shards by EPMA showed that the predominant composition of the tephra was andesite with occasional basaltic andesite pyroclasts. These results strongly correlated with the composition of tephra from the surrounding area, suggesting they are a product of the same volcanic eruptions (Palais *et al*., 1989b; Björck *et al*., 1991a; b; c; Björck *et al*., 1993; Aristarain and Delmas, 1998; Björck and Zale, 1998; Hodgson *et al*., 1998; Fretzdorff and Smellie, 2002). Extensive comparisons of Limnopolar Lake tephra with Holocene volcanic sources from around the Antarctic found that Deception Island eruptions were the probable source of most Limnopolar Lake tephra, a conclusion also reached for

tephra of similar compositions from the surrounding area (Palais *et al*., 1989b; Björck *et al*., 1991a; b; c; Björck *et al*., 1993; Aristarain and Delmas, 1998; Björck and Zale, 1998; Hodgson *et al*., 1998; Fretzdorff and Smellie, 2002). However, the lack of minor and trace mineral analyses of tephra in this study made it impossible to correlate tephra deposits with specific Deception Island eruptions. This problem was enhanced by Deception Island having a long history of erupting magmas with very little compositional variations (Matthies *et al*., 1988; Fretzdorff and Smellie, 2002).

Existing named tephras within the northern Antarctic Peninsular region are poorly described. Varying analytical techniques have been applied and the results presented in a wide variety of formats. This has made it difficult to understand the current tephrostratigraphy and tephrochronology of the area and has led to inaccurate naming of tephra horizons and subsequent correlations (Hodgson *et al*., 1998; Smellie, 1999; Beierle and Bond, 2002). Rigorous controls should be exerted on the analytical procedures for tephra analysis and on consistent statistical methods used in the presentation of data (Smellie, 1999). This will enable coherent and accurate tephra interpretations and correlations.

Little research has been carried out regarding the impacts that tephra has on lake communities, despite the fact that tephra has been documented to have profound ecological impacts (Abella, 1988; Heinrichs *et al*., 1999; Tatur *et al*., 1999; Baker *et al*., 2000). Tephra deposits in Limnopolar Lake have had some influences on biota throughout the lake's history, and have probably played a major role in shaping the lake's present ecology.

The biota within the lake has adapted to surviving background tephra levels (~30,000 g_{dm}^{-1}). Few species, in particular *Dactylobiotus* cf. *ambiguus* and *Parochlus steinenii*, have adapted to surviving slightly higher tephra loads (~45,000 g_{dm}^{-1}) and are present throughout the history of the lake. However, it is evident that all organisms are affected when tephra levels exceed ~45,000 g_{dm}^{-1}. These large tephra inputs tend to create a recovery period between 50-150 years before lake biota resumes its pre-tephra abundances.

Due to large inputs of tephra into lakes of the Antarctic Peninsula resulting in varying impacts on the lake environment and its ecology, it is difficult to identify other variables, such as climate, that my be causing fluctuations of ecology and productivity (Smellie, 1999). However, seven separate communities shifts have been identified within the biota preserved in the sediment core from Limnopolar Lake. Some of these ecosystem shifts appear to be driven by tephra loadings into the lake, while at least one ecosystem shift may be attributed to a regional climate change and another shift may be attributed to the grazing pressures created by the colonisation of the lake by *Branchinecta gainii*. It is difficult to reconstruct lake histories as only partial amounts of information are retained within sediment cores. Palaeolimnologists, therefore, must consider all of the abiotic and biotic factors of a lake, as well as a general understanding of the surrounding catchment area of the lake, so that assumptions may be made on certain variables that may be producing changes within the lake environment over time.

The tephra quiescence period from 0-250 years BP has provided a relatively stable environment, which has been reflected by the introduction of new species into the lake and an increase in the overall productivity. It will be interesting to investigate future tephra inputs into the lake to examine the response of this new ecosystem and whether it may lead to lake level extinctions of some of these organisms that might be less adapted to tephral input.

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Appendix 1

EPMA SHARD ANALYSES RESULTS

Depth (cm)	SiO_2	P_2O_5	TiO_2	Al_2O_3	MgO	CaO	MnO	FeO	Na_2O	K_2O	Total
0.2	56.68	0.41	1.69	16.26	4.06	7.47	0.20	7.83	4.68	0.71	95.80
0.2	56.32	0.34	1.64	16.45	4.20	7.97	0.07	7.52	4.75	0.75	94.03
0.2	55.62	0.33	1.58	16.51	4.25	8.04	0.14	8.06	4.69	0.78	95.44
0.2	52.36	0.19	1.33	21.94	2.99	11.15	0.12	5.29	4.30	0.34	97.34
0.2	52.66	0.25	1.55	20.39	3.33	10.44	0.19	6.43	4.30	0.47	95.92
0.2	51.60	0.36	2.27	14.49	6.77	8.99	0.18	10.50	4.15	0.70	95.63
0.2	53.42	0.50	2.95	14.66	3.83	7.92	0.22	11.30	4.56	0.66	95.96
0.2	52.84	0.43	2.97	14.39	4.09	7.82	0.11	11.83	4.94	0.59	93.26
0.2	52.72	0.44	2.89	14.88	3.98	8.00	0.26	11.52	4.68	0.63	95.86
0.2	56.02	0.24	1.64	16.78	4.22	7.88	0.05	7.75	4.68	0.73	95.06
0.2	56.13	0.23	1.61	16.42	4.27	7.94	0.19	8.04	4.54	0.63	95.14
0.2	55.60	0.18	1.62	17.00	4.23	8.35	0.11	7.62	4.61	0.69	95.29
0.6	54.47	0.36	2.24	15.66	4.03	8.20	0.19	10.14	4.10	0.36	100.15
0.6	57.17	0.49	2.80	14.14	2.94	6.42	0.23	11.09	3.73	0.49	99.77
1.0	54.78	0.25	1.62	17.02	4.53	8.66	0.18	8.28	4.10	0.57	100.44
1.0	56.24	0.28	1.63	16.93	4.08	7.78	0.17	8.18	4.03	0.66	99.66
1.4	54.43	0.23	1.49	15.75	6.37	9.64	0.18	7.98	3.49	0.44	99.76
1.4	55.39	0.28	1.72	16.60	4.43	8.32	0.16	8.49	4.00	0.60	99.70
1.4	55.21	0.33	1.87	15.42	4.54	8.22	0.19	9.33	4.22	0.67	100.22
1.8	53.46	0.19	1.45	20.35	2.93	9.73	0.10	6.65	4.69	0.45	97.50
1.8	54.18	0.20	1.49	19.01	3.32	9.66	0.20	6.76	4.70	0.49	96.93
1.8	54.02	0.23	1.46	19.38	3.25	9.77	0.17	6.82	4.45	0.44	96.12
1.8	55.31	0.25	1.62	16.85	4.09	8.16	0.13	8.15	4.76	0.68	95.69
1.8	55.47	0.30	1.33	18.18	3.47	8.88	0.10	6.96	4.64	0.66	94.30
1.8	56.11	0.21	1.53	16.60	3.98	7.83	0.21	8.12	4.61	0.82	94.70
1.8	57.26	0.63	3.16	12.73	2.44	5.59	0.22	12.65	4.07	1.23	100.40
2.2	54.84	0.29	1.87	15.28	4.84	8.74	0.21	9.24	3.99	0.69	98.89
2.2	62.50	0.54	1.86	15.51	1.71	4.36	0.18	7.64	4.48	1.23	99.90
2.2	51.53	0.24	1.85	16.10	6.07	10.78	0.16	9.17	3.73	0.33	98.90
2.6	55.47	0.30	1.77	16.22	4.40	7.80	0.19	8.97	4.13	0.72	100.15
2.6	55.47	0.27	1.60	17.12	4.26	8.41	0.17	8.02	4.07	0.60	99.48
2.6	56.24	0.52	2.65	15.65	3.48	7.06	0.21	10.49	2.99	0.70	97.81
3.0	57.03	0.28	1.60	16.89	3.86	7.55	0.16	7.90	4.03	0.72	100.02
3.0	56.81	0.27	1.55	17.18	3.88	7.55	0.16	7.75	4.15	0.70	100.31
3.0	55.18	0.25	1.59	17.19	4.30	8.48	0.18	8.26	3.95	0.60	99.30
3.4	54.93	0.26	1.77	17.15	4.19	8.55	0.16	8.44	3.97	0.58	99.87
3.4	56.56	0.41	2.90	13.83	3.25	6.84	0.25	11.58	3.46	0.91	98.60
3.4	53.34	0.28	1.90	15.71	5.32	9.66	0.17	9.22	3.93	0.47	99.81

Depth (cm)	SiO_2	P_2O_5	TiO_2	Al_2O_3	MgO	CaO	MnO	FeO	Na_2O	K_2O	Total
3.8	56.00	0.30	1.58	16.54	4.00	8.18	0.18	7.98	4.44	0.79	94.92
3.8	55.43	0.34	1.61	16.80	4.20	7.97	0.20	8.09	4.68	0.67	94.70
3.8	56.23	0.22	1.61	16.38	4.03	8.10	0.16	8.01	4.50	0.77	94.72
3.8	54.47	0.24	1.46	19.76	2.59	9.65	0.07	6.57	4.69	0.50	96.74
3.8	54.73	0.28	1.79	17.64	3.18	9.24	0.10	7.63	4.86	0.54	95.96
3.8	54.26	0.15	0.72	24.19	1.26	10.85	0.07	3.60	4.69	0.23	97.80
3.8	54.52	0.28	2.29	15.37	4.21	7.79	0.19	10.17	4.41	0.76	94.74
3.8	54.53	0.34	2.27	14.58	4.06	8.03	0.20	10.43	4.79	0.77	95.49
3.8	54.70	0.32	2.13	16.31	3.63	8.18	0.17	9.38	4.59	0.58	95.06
3.8	55.71	0.37	1.68	16.53	4.21	8.38	0.14	7.79	4.48	0.71	96.42
3.8	55.90	0.28	1.59	17.10	4.09	7.88	0.18	7.50	4.65	0.84	97.72
3.8	56.98	0.26	1.60	16.67	4.17	7.68	0.19	7.28	4.48	0.69	95.96
3.8	56.09	0.25	1.66	16.52	4.12	8.02	0.17	7.89	4.66	0.61	94.86
3.8	56.16	0.20	1.61	16.24	4.42	7.92	0.17	7.71	4.93	0.66	95.75
3.8	56.87	0.17	1.58	16.50	4.08	7.39	0.17	7.55	4.92	0.77	96.06
4.2	54.96	0.29	1.71	16.60	4.44	8.41	0.17	8.77	4.02	0.60	99.44
4.6	59.27	0.27	1.39	17.08	3.13	6.49	0.16	7.10	4.20	0.90	100.74
4.6	57.17	0.42	2.42	15.13	2.58	6.51	0.20	10.36	4.21	0.99	98.53
5.0	51.83	0.07	1.04	3.98	16.27	16.21	0.31	9.54	0.60	0.08	99.95
5.0	57.24	0.29	1.66	16.68	3.84	7.38	0.18	8.12	3.83	0.77	99.01
5.0	53.07	0.35	1.89	14.48	6.66	4.87	0.29	14.05	3.88	0.47	100.02
5.4	56.68	0.49	2.81	14.35	3.22	6.74	0.22	10.97	3.57	0.94	99.44
5.4	53.15	0.17	1.33	22.54	1.72	10.31	0.12	5.81	4.61	0.24	100.27
5.8	57.30	0.29	1.60	17.04	3.63	7.37	0.16	7.72	4.18	0.71	99.60
5.8	55.53	0.50	2.67	15.44	3.53	6.74	0.23	10.74	3.86	0.76	99.71
5.8	55.71	0.18	1.24	18.70	3.31	9.28	0.11	6.10	4.83	0.53	96.90
5.8	55.81	0.27	1.62	16.66	4.15	8.37	0.23	7.61	4.52	0.75	96.55
5.8	56.08	0.30	1.63	16.65	4.27	7.99	0.21	7.72	4.46	0.69	96.49
6.2	58.63	0.48	2.75	14.90	2.45	6.00	0.21	9.72	3.77	1.10	98.78
6.2	55.69	0.27	1.54	17.13	4.14	8.12	0.18	7.99	4.29	0.64	100.17
6.6	55.12	0.23	1.44	18.40	3.69	8.81	0.15	7.34	4.33	0.49	99.35
6.6	55.60	0.27	1.61	17.02	4.19	8.38	0.16	7.98	4.17	0.61	99.74
7.0	54.72	0.27	1.72	16.78	4.65	8.55	0.18	8.57	3.99	0.57	99.34
7.8	56.14	0.12	1.75	16.17	4.20	8.02	0.21	8.22	4.51	0.65	95.60
7.8	55.66	0.32	1.70	16.43	4.15	7.88	0.15	8.16	4.73	0.83	95.18
7.8	55.61	0.23	1.65	16.31	4.31	7.93	0.14	8.37	4.75	0.69	95.78
7.8	55.22	0.32	1.69	16.07	4.53	8.17	0.14	8.28	4.80	0.78	96.94
7.8	55.61	0.24	1.68	16.19	4.38	7.79	0.11	8.37	4.98	0.66	96.07
7.8	54.87	0.32	1.71	16.16	4.41	8.34	0.25	8.47	4.82	0.65	96.72
7.8	55.90	0.22	1.58	16.46	4.46	7.93	0.20	7.70	4.86	0.67	96.15
7.8	56.45	0.26	1.63	16.61	4.00	7.65	0.13	7.68	4.79	0.80	96.77
7.8	56.24	0.28	1.63	16.25	4.18	7.89	0.10	8.18	4.57	0.69	95.75
8.2	53.11	0.28	1.99	15.40	5.41	9.70	0.19	9.52	3.91	0.48	98.59
8.2	52.12	0.28	1.75	15.80	6.23	10.49	0.19	8.90	3.78	0.43	98.46
8.6	54.10	0.27	1.67	18.94	2.98	9.36	0.16	7.62	4.40	0.50	99.42
8.6	56.88	0.28	1.44	17.98	3.31	7.84	0.15	6.92	4.59	0.61	99.43
8.6	54.47	0.00	0.13	27.96	0.14	11.25	0.00	0.93	5.00	0.12	99.21
9.0	55.70	0.28	1.58	17.05	4.12	8.07	0.16	8.10	4.31	0.63	99.95

Depth (cm)	SiO_2	P_2O_5	TiO_2	Al_2O_3	MgO	CaO	MnO	FeO	Na_2O	K_2O	Total
9.0	55.84	0.45	2.84	14.51	3.24	7.65	0.21	10.71	3.71	0.84	98.52
9.0	55.40	0.27	1.57	17.21	4.19	8.42	0.15	8.01	4.18	0.59	99.13
9.4	55.34	0.29	1.59	17.12	4.23	8.24	0.17	8.23	4.15	0.62	98.52
9.4	56.11	0.26	1.58	17.30	4.07	7.91	0.16	7.84	4.14	0.62	99.02
9.8	57.55	0.46	2.44	14.69	3.16	6.54	0.20	9.92	4.11	0.91	100.26
9.8	56.25	0.19	1.65	16.58	4.03	8.16	0.19	7.75	4.74	0.47	94.70
9.8	55.96	0.29	1.53	16.42	4.08	7.97	0.09	8.25	4.65	0.76	95.15
9.8	55.77	0.24	1.60	16.38	4.12	8.05	0.15	7.99	4.92	0.79	95.62
9.8	56.02	0.24	1.64	16.78	4.22	7.88	0.05	7.75	4.68	0.73	95.06
9.8	56.13	0.23	1.61	16.42	4.27	7.94	0.19	8.04	4.54	0.63	95.14
9.8	55.60	0.18	1.62	17.00	4.23	8.35	0.11	7.62	4.61	0.69	95.29
10.0	55.78	0.26	1.54	17.31	4.13	8.09	0.16	7.85	4.25	0.62	99.72
10.5	55.51	0.27	1.67	16.74	4.27	8.29	0.17	8.29	4.16	0.61	99.33
10.5	54.84	0.17	1.19	22.24	1.52	9.63	0.10	5.06	4.87	0.36	99.99
11.0	54.64	0.26	1.58	17.04	4.36	8.71	0.18	8.42	4.20	0.60	98.83
11.0	56.40	0.28	1.52	17.42	3.73	7.83	0.15	7.64	4.37	0.67	99.22
11.5	58.11	0.17	0.76	21.80	1.50	8.15	0.08	3.45	5.59	0.38	99.61
11.5	57.32	0.50	2.93	13.84	2.98	6.54	0.21	11.04	3.68	0.96	99.76
12.5	55.64	0.29	1.66	16.88	4.21	8.06	0.17	8.23	4.22	0.66	99.36
12.5	55.40	0.25	1.66	20.12	2.19	9.19	0.10	5.35	5.40	0.35	100.43
12.5	55.90	0.53	2.97	14.53	2.57	6.91	0.21	11.07	4.36	0.93	97.25
13.0	56.68	0.41	1.69	16.26	4.06	7.47	0.20	7.83	4.68	0.71	99.70
13.0	56.32	0.34	1.64	16.45	4.20	7.97	0.07	7.52	4.75	0.75	98.75
13.5	57.18	0.52	2.63	18.10	2.18	6.74	0.13	7.19	4.69	0.63	98.10
13.5	56.03	0.29	1.61	17.01	4.05	7.75	0.16	8.06	4.36	0.66	99.62
13.5	55.93	0.27	1.57	17.10	3.99	7.88	0.17	7.96	4.47	0.65	99.58
14.0	55.91	0.29	1.56	17.25	4.03	8.14	0.17	7.76	4.22	0.65	99.04
14.5	54.37	0.42	2.83	14.02	3.74	7.68	0.21	11.88	4.08	0.76	99.50
14.5	55.75	0.27	1.80	18.14	2.37	8.37	0.15	7.73	4.95	0.46	99.28
14.5	48.46	0.35	1.62	10.76	13.21	5.06	0.29	16.84	2.93	0.47	101.10
15.0	53.08	0.41	2.75	13.83	4.82	8.47	0.22	11.68	4.13	0.60	98.49
15.0	54.38	0.40	2.57	14.12	4.01	8.37	0.22	11.19	4.01	0.70	99.79
15.0	53.99	0.38	2.21	14.90	4.72	8.69	0.21	10.25	4.05	0.61	99.37
15.5	54.74	0.38	2.28	15.96	3.87	7.79	0.20	9.82	4.29	0.67	99.76
15.5	52.56	0.40	2.56	15.22	4.54	8.60	0.20	11.10	4.29	0.50	99.27
15.5	55.44	0.40	2.49	15.24	3.14	7.57	0.21	10.43	4.36	0.73	99.39
16.0	51.14	0.34	2.16	15.72	5.83	10.12	0.18	10.03	3.89	0.57	98.48
16.0	54.28	0.44	2.74	13.92	4.26	8.10	0.23	11.47	3.81	0.73	98.74
16.0	53.62	0.32	2.19	15.85	3.96	8.19	0.19	10.74	4.14	0.78	99.36
16.5	54.06	0.34	2.16	15.74	4.19	8.59	0.17	9.91	4.21	0.63	99.26
16.5	56.30	0.37	2.32	16.93	2.49	7.37	0.16	8.58	4.83	0.63	95.24
17.0	49.48	0.02	0.06	31.45	0.10	14.95	0.01	0.78	3.11	0.05	100.02
17.5	54.45	0.35	2.14	15.43	4.25	8.47	0.19	10.00	4.09	0.63	99.10
17.5	54.57	0.35	2.39	15.45	3.44	7.95	0.20	10.56	4.41	0.68	99.51
18.0	54.73	0.41	2.66	14.03	3.91	7.70	0.22	11.42	4.12	0.80	99.91
18.0	54.47	0.21	1.31	21.90	1.15	9.67	0.10	5.96	4.87	0.35	100.54
18.5	54.90	0.40	2.46	14.72	3.65	7.80	0.21	10.93	4.18	0.74	99.25
18.5	55.29	0.36	2.16	16.33	3.19	7.33	0.17	9.52	5.36	0.27	99.77

Depth (cm)	SiO_2	P_2O_5	TiO_2	Al_2O_3	MgO	CaO	MnO	FeO	Na_2O	K_2O	Total
19.0	54.90	0.32	2.09	17.76	2.56	8.41	0.17	8.56	4.68	0.55	99.65
19.0	49.42	0.38	1.61	12.30	11.90	5.81	0.25	14.68	3.18	0.47	99.69
19.0	54.27	0.33	2.36	15.22	4.02	8.41	0.22	10.29	4.21	0.65	99.90
19.5	54.40	0.39	2.52	14.78	3.83	8.34	0.21	10.66	4.15	0.69	99.42
20.0	55.04	0.42	2.70	14.05	3.65	7.49	0.23	11.59	4.06	0.76	99.80
20.0	54.75	0.11	0.66	24.88	0.77	10.27	0.05	3.11	5.15	0.25	100.21
20.0	56.21	0.26	1.58	17.18	3.89	7.87	0.16	7.96	4.20	0.66	99.35
20.5	55.39	0.26	1.53	17.13	4.23	8.36	0.15	8.07	4.27	0.60	99.52
20.5	55.71	0.27	1.61	17.15	4.17	8.14	0.16	8.08	4.10	0.62	99.09
20.5	53.67	0.07	0.27	28.15	0.17	11.65	<0.00	1.23	4.69	0.11	100.21
21.0	55.34	0.28	1.68	16.65	4.35	8.17	0.17	8.58	4.16	0.63	99.71
21.0	53.15	0.23	1.42	20.72	2.58	10.12	0.12	6.90	4.38	0.36	100.57
21.5	56.27	0.29	1.98	20.12	2.01	7.55	0.16	6.30	4.62	0.69	99.83
21.5	54.32	0.42	2.72	13.04	4.57	8.11	0.25	11.91	3.92	0.74	99.88
22.0	54.76	0.27	1.78	16.07	4.72	8.34	0.20	9.22	4.01	0.62	98.70
22.5	51.16	0.36	2.22	15.61	5.64	10.10	0.21	10.13	3.96	0.59	98.92
22.5	54.93	0.25	1.59	17.23	4.37	8.53	0.17	8.19	4.16	0.57	99.27
23.0	55.89	0.27	1.54	17.18	3.95	8.00	0.17	7.91	4.42	0.65	99.45
23.0	55.37	0.30	1.79	16.41	4.42	7.87	0.18	8.68	4.28	0.70	99.76
23.0	60.29	0.48	1.92	15.94	2.32	5.17	0.19	8.38	4.27	1.05	100.30
23.5	54.71	0.38	2.56	14.53	3.61	7.76	0.22	11.27	4.24	0.71	99.55
23.5	55.19	0.28	1.67	16.73	4.39	8.25	0.18	8.41	4.28	0.62	99.39
24.0	55.62	0.28	1.61	16.97	4.09	8.11	0.17	8.17	4.33	0.64	99.62
24.0	54.84	0.26	1.48	18.20	3.69	8.73	0.15	7.60	4.51	0.55	100.03
24.5	54.54	0.27	1.57	19.90	2.79	8.43	0.12	7.20	4.72	0.45	101.13
25.0	54.91	0.04	0.34	26.56	0.39	10.70	0.00	1.86	5.04	0.16	99.59
26.0	51.83	0.03	0.07	29.93	0.15	13.42	0.00	0.59	3.91	0.07	99.60
26.0	55.69	0.28	1.58	17.03	4.15	8.17	0.15	8.04	4.28	0.63	98.70
27.0	55.56	0.29	1.57	17.06	4.16	8.21	0.17	8.15	4.21	0.62	99.10
27.0	55.22	0.52	2.89	13.87	3.67	7.38	0.25	11.62	3.67	0.91	98.77
27.0	54.49	0.53	3.03	13.79	3.53	7.30	0.23	12.42	3.97	0.71	99.50
28.0	55.95	0.26	1.57	17.22	4.03	7.95	0.17	7.91	4.29	0.65	99.60
28.0	54.05	0.50	3.09	13.97	3.64	7.40	0.25	12.50	3.90	0.69	99.33
28.0	54.40	0.40	2.31	15.81	4.08	7.85	0.18	10.17	4.17	0.63	99.27

Appendix 2

RESULTS FROM THE CONISS CLUSTER ANALYSES

Clusters merged	Increase in dispersion	Total dispersion	Within cluster dispersion	Mean within cluster dispersion
24-25	0.0000411	0.0000411	0.0000411	0.0000206
3-4	0.0091650	0.0092061	0.009165	0.0045825
6-7	0.0181524	0.0273585	0.0181524	0.0090762
38-39	0.0201542	0.0475127	0.0201542	0.0100771
37-38	0.0201076	0.0676203	0.0402618	0.0134206
17-18	0.0232387	0.0908590	0.0232387	0.0116194
2-3	0.0330913	0.1239503	0.0422562	0.0140854
5-6	0.0367397	0.1606900	0.0548921	0.0182974
37-40	0.0371014	0.1977914	0.0773632	0.0193408
17-19	0.0429272	0.2407186	0.0661659	0.0220553
17-20	0.0438390	0.2845576	0.1100049	0.0275012
17-21	0.0298969	0.3144544	0.1399018	0.0279804
41-42	0.0493294	0.3637838	0.0493294	0.0246647
37-41	0.0537587	0.4175426	0.1804513	0.0300752
35-36	0.0547628	0.4723054	0.0547628	0.0273814
5-8	0.0573420	0.5296474	0.1122341	0.0280585
22-23	0.0606803	0.5903277	0.0606803	0.0303402
13-14	0.0616439	0.6519715	0.0616439	0.0308219
35-37	0.0653094	0.7172809	0.3005235	0.0375654
10-11	0.0723903	0.7896712	0.0723903	0.0361951
30-31	0.0753537	0.8650249	0.0753537	0.0376769
15-16	0.0815296	0.9465545	0.0815296	0.0407648
29-30	0.1023463	1.0489008	0.1777000	0.0592333
34-35	0.1046292	1.1535301	0.4051528	0.0450170
33-34	0.1237050	1.2772352	0.5288578	0.0528858
32-33	0.0324515	1.3096867	0.5613093	0.0510281
10-12	0.1251505	1.4348371	0.1975408	0.0658469
5-9	0.1373667	1.5722038	0.2496008	0.0499202
13-15	0.1731554	1.7453592	0.3163289	0.0790822
26-27	0.1984677	1.9438269	0.1984677	0.0992338
1-2	0.2042129	2.1480398	0.2464691	0.0616173
28-29	0.2610014	2.4090412	0.4387014	0.1096753
28-32	0.1774969	2.5865381	1.1775075	0.0785005
22-24	0.2838259	2.8703640	0.3445474	0.0861368
1-5	0.7564787	2.6268427	1.2525486	0.1391721
10-13	1.0663761	4.6932187	1.5802457	0.2257494
10-17	0.8725417	5.5657606	2.5926893	0.2160574
10-22	1.0029703	6.5687308	3.9402070	0.2462629
10-26	1.2123653	7.7810960	5.3510399	0.2972800
1-10	2.1219754	9.9030714	8.7255640	0.3231690
1-28	3.2695558	13.1726274	13.1726274	0.3136340

The clusters represent the sample number labelled from the top of the core; if two samples are merged they are then referred to by the uppermost merged sample.

Appendix 3

COMPOSITION OF HOLOCENE VOLCANIC CENTRES FROM THE ANTARCTIC AND LIMNOPOLAR LAKE TEPHRA

A.3.1 Alexander Land, Palmer Land, and Ellsworth Land

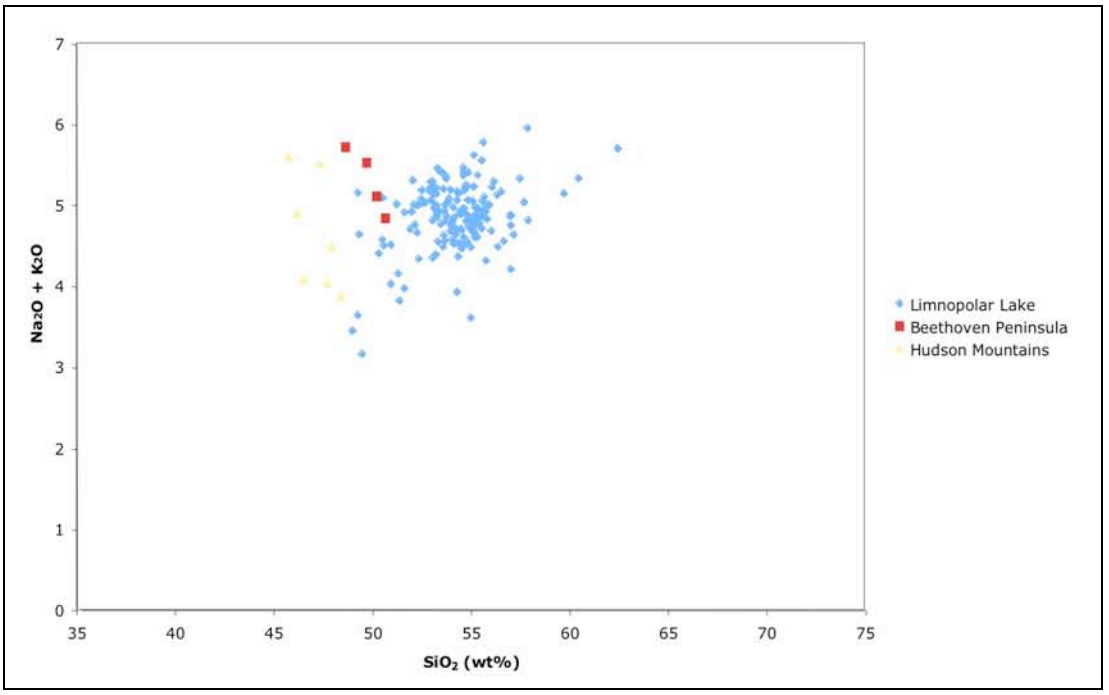

Figure A.3.1.1 Sum of Na_2O and K_2O vs. SiO_2 for Holocene volcanic rocks from Alexander Land, Palmer Land, Ellsworth Land, and for Limnopolar Lake tephra shards (all bulk rock analyses extracted from various sources in LeMasurier and Thomson, 1990).

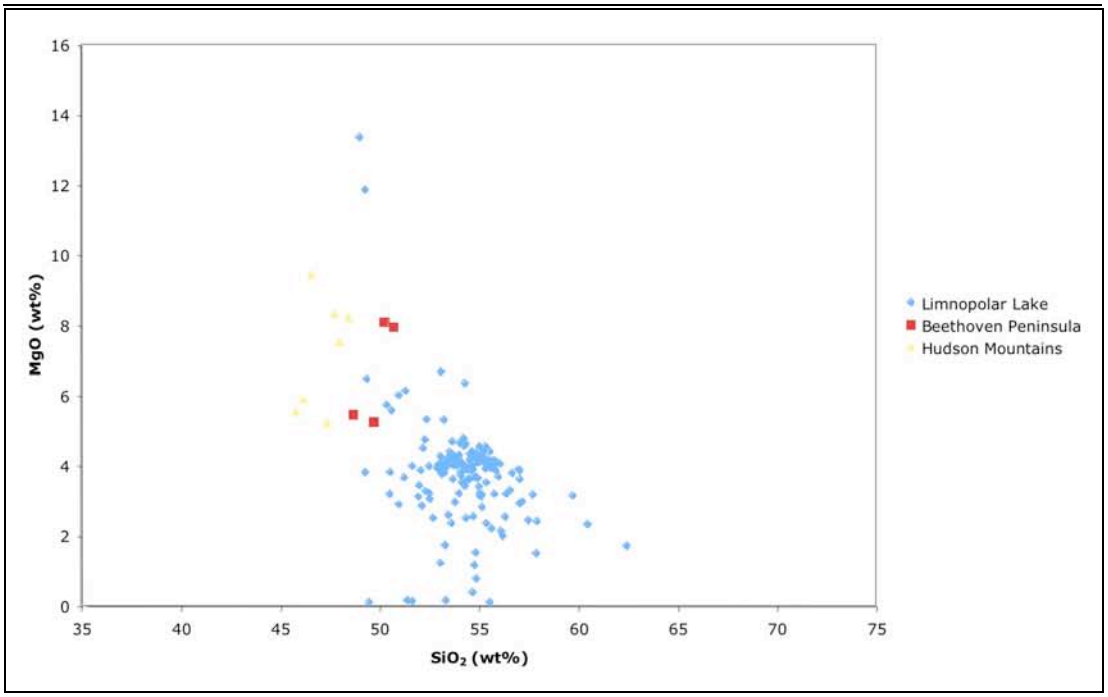

Figure A.3.1.2 MgO vs. SiO_2 for Holocene volcanic rocks from Alexander Land, Palmer Land, Ellsworth Land, and for Limnopolar Lake tephra shards (all bulk rock analyses extracted from various sources in LeMasurier and Thomson, 1990).

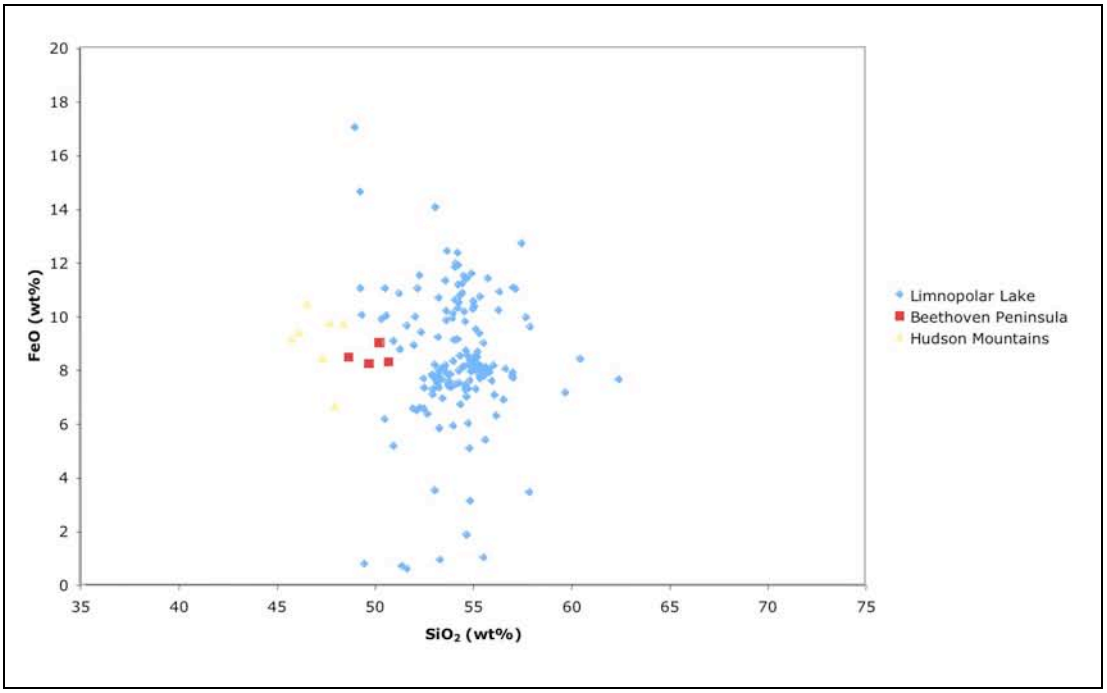

Figure A.3.1.3 FeO vs. SiO_2 for Holocene volcanic rocks from Alexander Land, Palmer Land, Ellsworth Land, and for Limnopolar Lake tephra shards (all bulk rock analyses extracted from various sources in LeMasurier and Thomson, 1990).

A.3.2 Marie Byrd Land

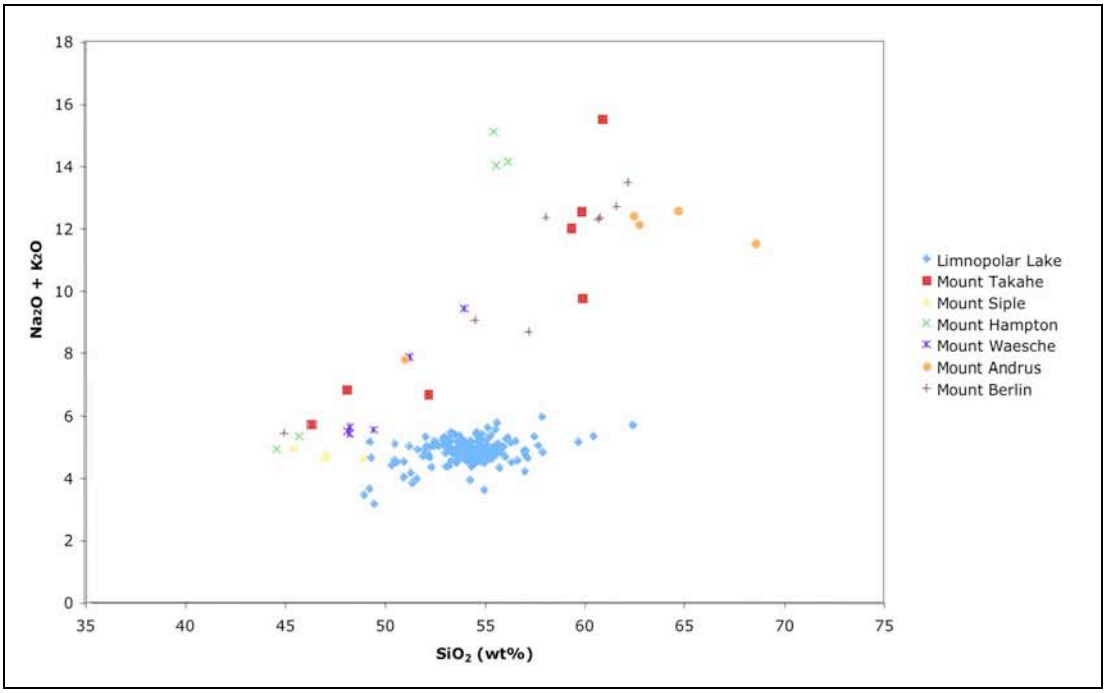

Figure A.3.2.1. Sum of Na_2O and K_2O vs. SiO_2 for Holocene volcanic rocks from Marie Byrd Land and for Limnopolar Lake tephra shards (all bulk rock analyses extracted from various sources in LeMasurier and Thomson, 1990).

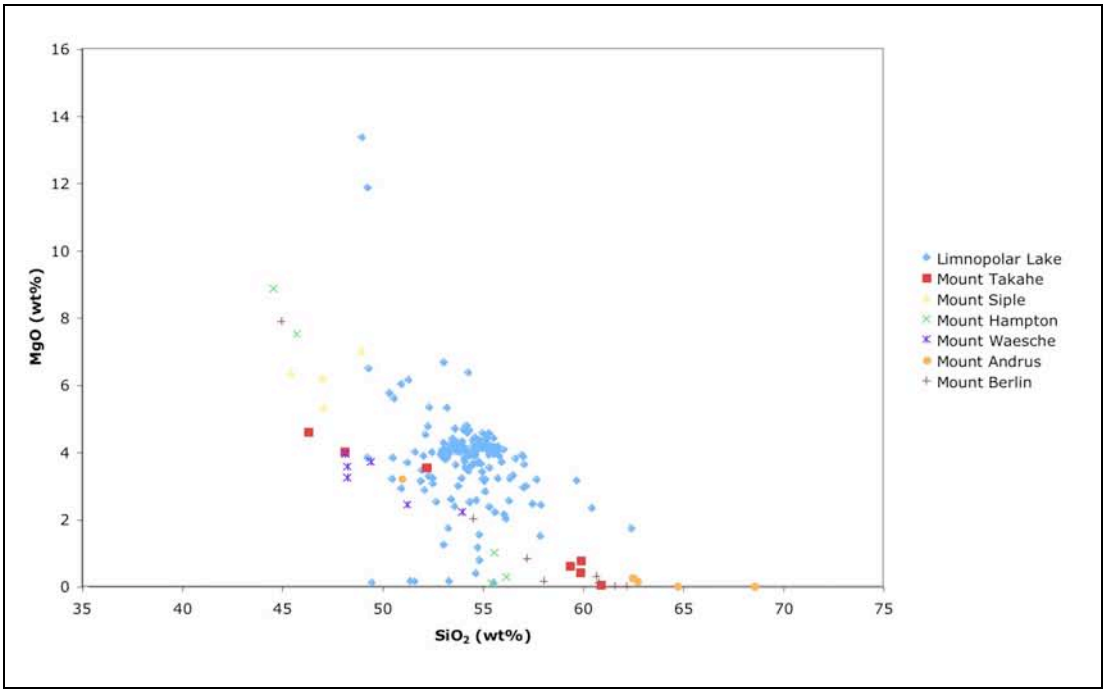

Figure A.3.2.2. MgO vs. SiO_2 for Holocene volcanic rocks from Marie Byrd Land and for Limnopolar Lake tephra shards (all bulk rock analyses extracted from various sources in LeMasurier and Thomson, 1990).

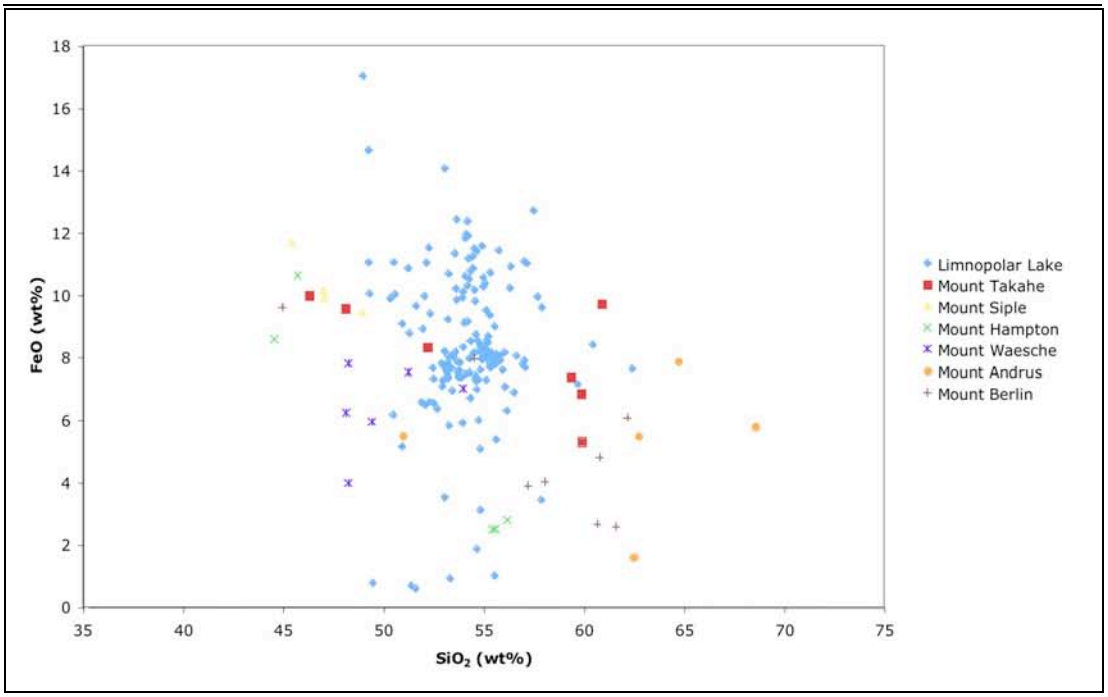

Figure A.3.2.3. FeO vs. SiO_2 for Holocene volcanic rocks from Marie Byrd Land and for Limnopolar Lake tephra shards (all bulk rock analyses extracted from various sources in LeMasurier and Thomson, 1990).

A.3.3 McMurdo Volcanic Group – Western Ross Embayment

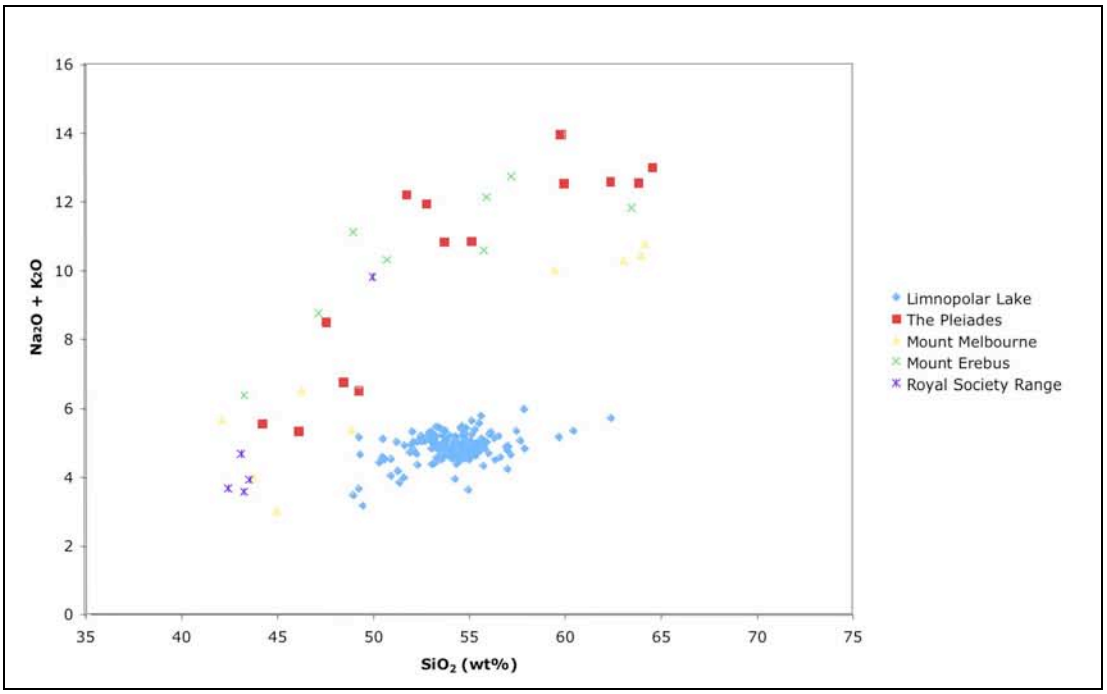

Figure A.3.3.1. Sum of Na_2O and K_2O vs. SiO_2 for Holocene volcanic rocks from the McMurdo Volcanic Group and for Limnopolar Lake tephra shards (all bulk rock analyses extracted from various sources in LeMasurier and Thomson, 1990).

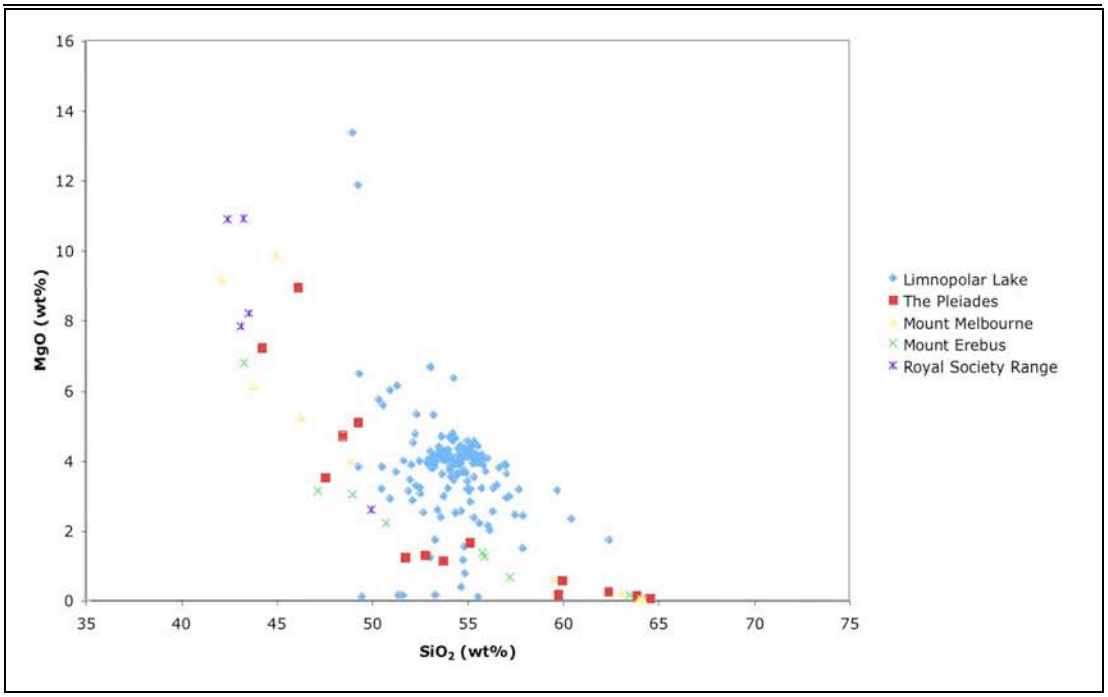

Figure A.3.3.2. MgO vs. SiO_2 for Holocene volcanic rocks from the McMurdo Volcanic Group and for Limnopolar Lake tephra shards (all bulk rock analyses extracted from various sources in LeMasurier and Thomson, 1990).

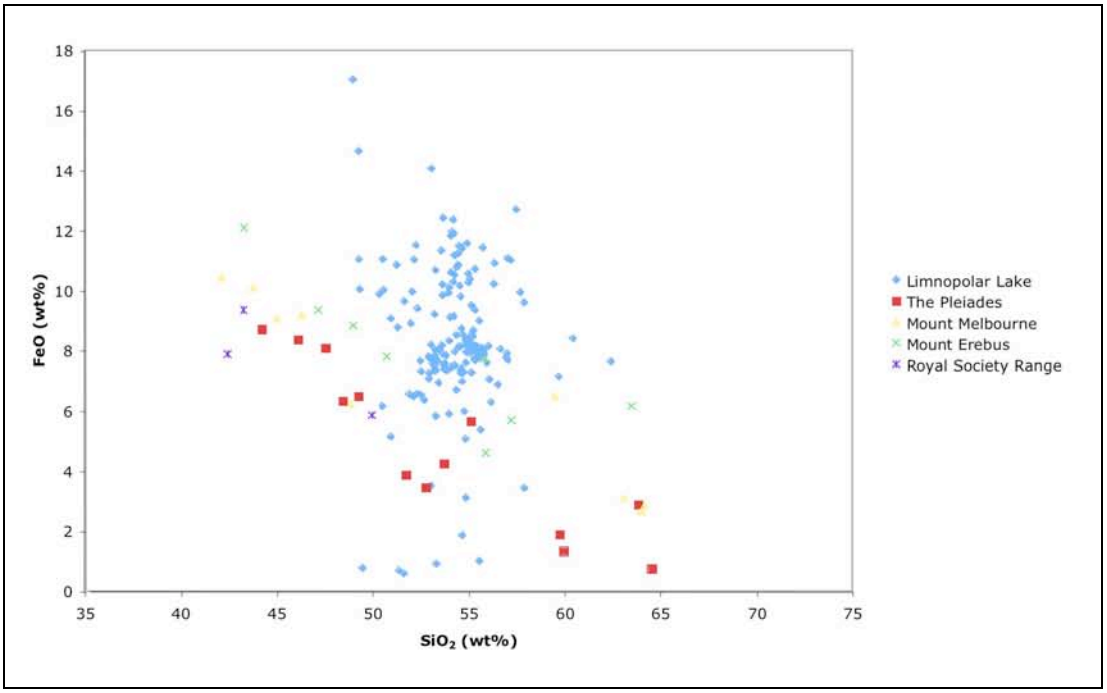

Figure A.3.3.3. FeO vs. SiO_2 for Holocene volcanic rocks from the McMurdo Volcanic Group and for Limnopolar Lake tephra shards (all bulk rock analyses extracted from various sources in LeMasurier and Thomson, 1990).

A.3.4 Oceanic Islands on the Antarctic Plate

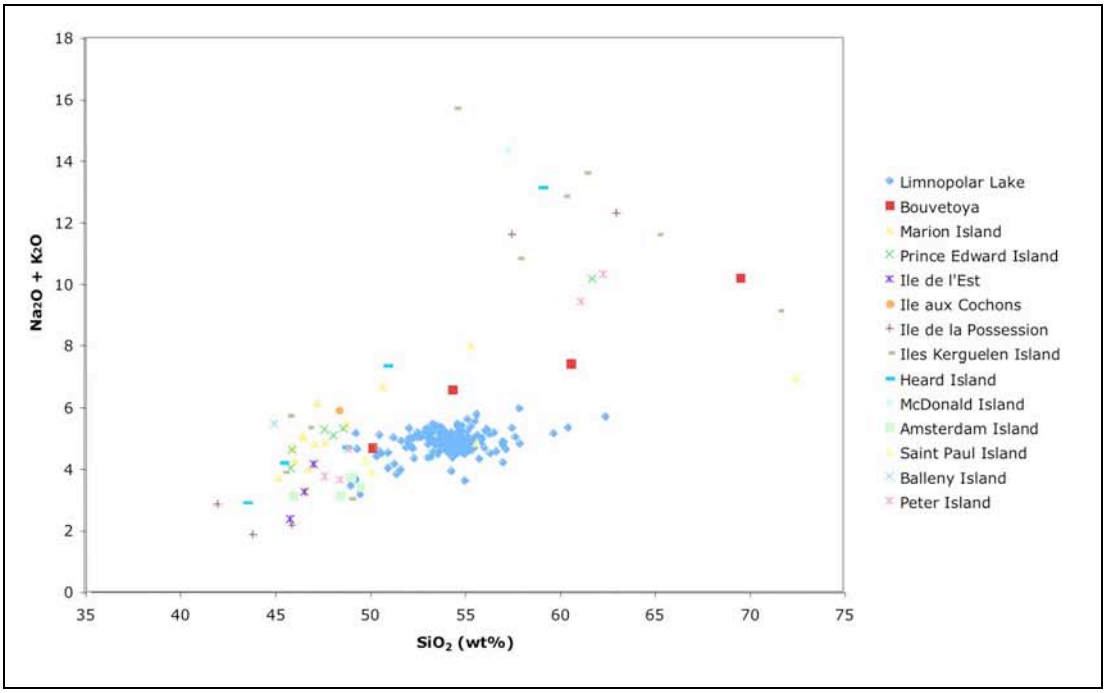

Figure A.3.4.1. Sum of Na_2O and K_2O vs. SiO_2 for Holocene volcanic rocks from the oceanic islands of the Antarctic Plate and for Limnopolar Lake tephra shards (all bulk rock analyses extracted from various sources in LeMasurier and Thomson, 1990).

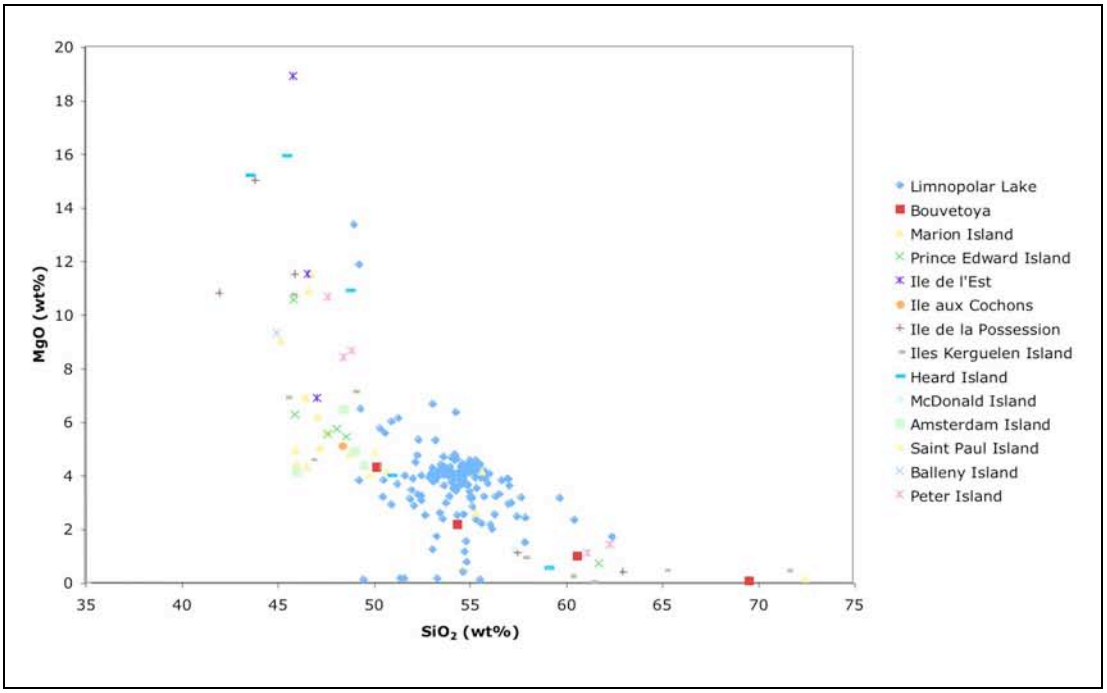

Figure A.3.4.2. MgO vs. SiO_2 for Holocene volcanic rocks from the oceanic islands of the Antarctic Plate and for Limnopolar Lake tephra shards (all bulk rock analyses extracted from various sources in LeMasurier and Thomson, 1990).

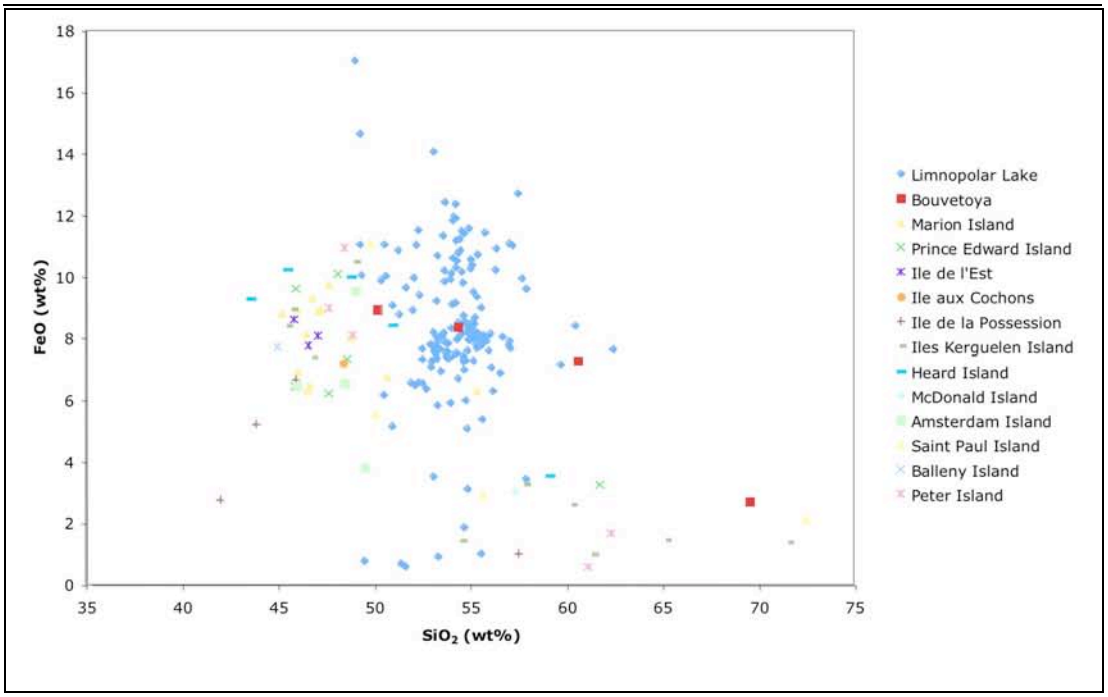

Figure A.3.4.3. FeO vs. SiO_2 for Holocene volcanic rocks from the oceanic islands of the Antarctic Plate and for Limnopolar Lake tephra shards (all bulk rock analyses extracted from various sources in LeMasurier and Thomson, 1990).

A.3.5 Subantarctic volcanoes of the Pacific Plate

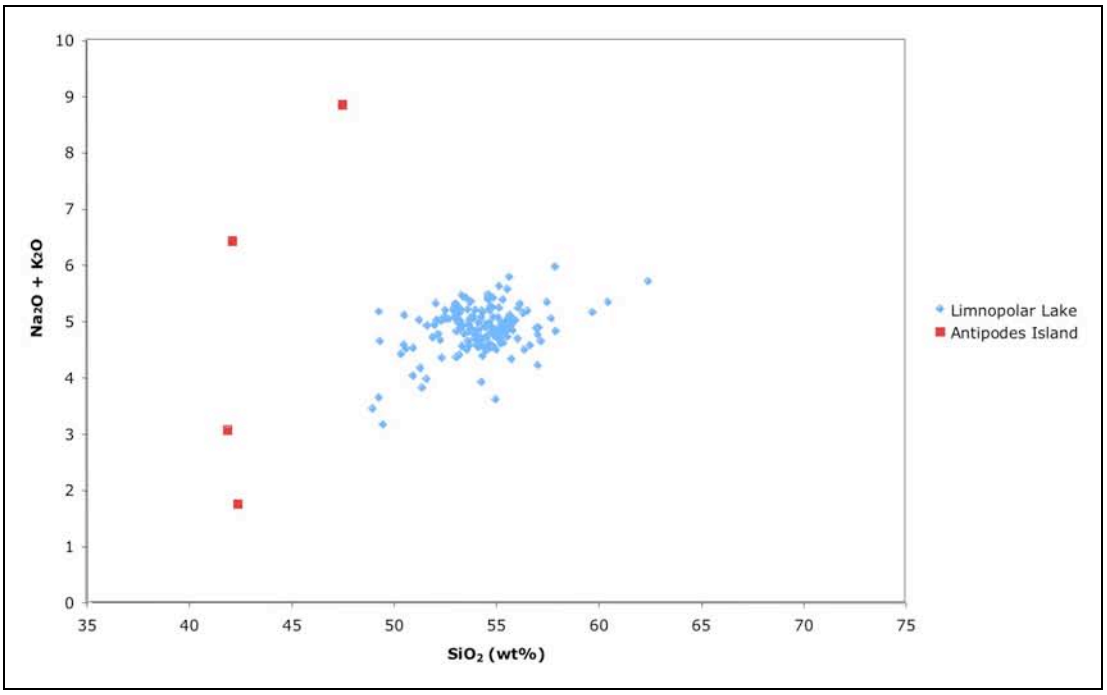

Figure A.3.5.1. Sum of Na_2O and K_2O vs. SiO_2 for Holocene volcanic rocks from the oceanic islands of the Pacific Plate and for Limnopolar Lake tephra shards (all bulk rock analyses extracted from various sources in LeMasurier and Thomson, 1990).

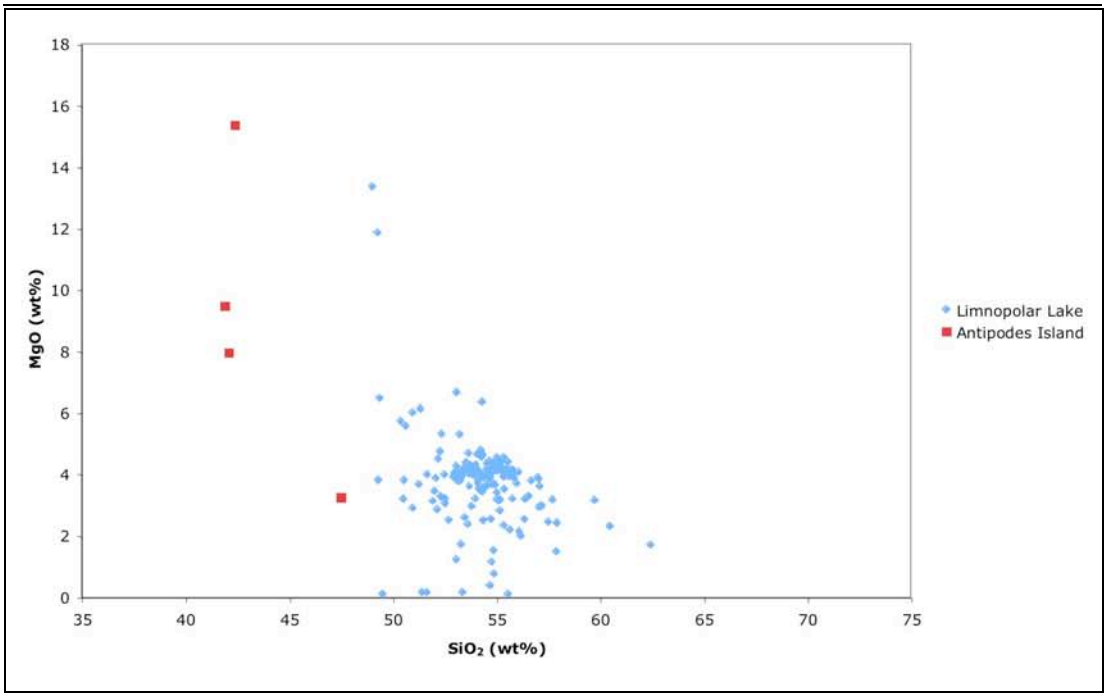

Figure A.3.5.2. MgO vs. SiO_2 for Holocene volcanic rocks from the oceanic islands of the Pacific Plate and for Limnopolar Lake tephra shards (all bulk rock analyses extracted from various sources in LeMasurier and Thomson, 1990).

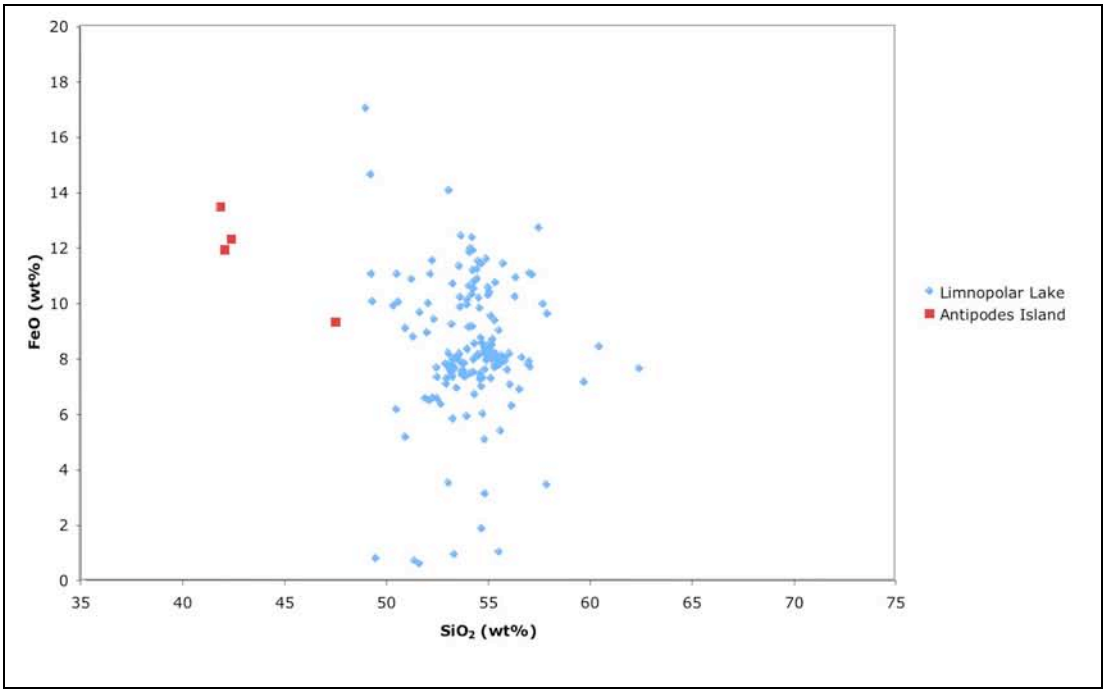

Figure A.3.5.3. FeO vs. SiO_2 for Holocene volcanic rocks from the oceanic islands of the Pacific Plate and for Limnopolar Lake tephra shards (all bulk rock analyses extracted from various sources in LeMasurier and Thomson, 1990).